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THE RE-ENFORCEMENT OF THE ANCHORAGE AND RENEWAL OF THE SUSPENDED SUPERSTRUCTURE OF THE NIAGARA RAILROAD SUSPENSION BRIDGE.

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Presented at the 13th Annual Convention, June 15th 1881.

Mr. President, and Gentlemen of the American Society of Civil Engineers : Having completed the work in question, I have, at the request of several of the members of the Society, prepared the following paper, believing that it will possess some points of interest to such members as are engaged in bridge building.

When the project of spanning the Niagara river with a suspension bridge for railroad purposes began to be discussed, grave doubts as to its practicability were expressed. This feeling was shared by some quite prominent engineers, till the work was very nearly ready for the passage of trains.

The bridge has now been in constant use for nearly twenty-six years. Yet to the traveling public it has always been an object of solicitude. The location of the bridge would naturally excite the fears of timid people who can only form an opinion based upon their faith in the man who undertakes to build a bridge in such a place, while even the more courageous and intelligent have felt that causes might be at work which would some time effect its destruction.

These fears finally led to a thorough inspection of the cables and of such portions of the anchorage as were accessible or would be liable to injury, and also to the subsequent re-enforcement and renewal which are the subjects of this paper.

Before entering upon an account of those operations it is necessary to give, for the benefit of those members who never visited the bridge in question, a general description of the structure as it was.

Description of Old Work.

I. *Locality.*—The bridge is about two miles below the Falls. The formation over which the Niagara river flows, and through which it is supposed to have cut its way, from a short distance above Lewiston to where the Falls now are, consists of nearly level strata of rock. These strata, from the surface to a depth of about one hundred and eighty feet, are principally composed of limestone. Underlying this portion is a bed of red sandstone about forty feet thick, or extending about to the surface of the water of the river.

The surface stratum is solid, especially on the New York side of the river, and has a thickness of about 15 feet in the vicinity of the anchorage. This is followed by a stratum of limestone shale, interspersed with flint. Following this is a solid stratum of rock about 20 feet to 30 feet thick.

The gorge at the level of the surface of the rock is about 730 feet wide measured on centre line of the bridge.

The surface of the rock on the Canada side is about 10 feet higher than that on the New York side.

II. *The Bridge.*—The general description of the bridge is as follows :

1st. Four cables, resting on the tops of two masonry towers at each end of the span, have their ends anchored to the rock.

The length of span between centres of towers is 821 feet.

Two of the cables at mean temperature have a versed sine of 54 feet, and are denominated upper cables.

The other two cables have a versed sine of 64 feet, and are called lower cables.

The planes of the curves of the cables on each side are inclined so as to bring their lowest points nearer together than they are at the tops of the towers. From the tops of the towers to the anchorage the cables diverge from the centre line sufficiently to make their pressure upon the towers vertical.

The portions of the cable on each side of the tower and adjacent to it form the same angle with the vertical. Hence the anchorage of the upper cable is about 37 feet further from the tower than that of the lower cable.

2d. Suspended superstructure. This consists of two floors, one above the other, connected together at each side by posts and truss rods, the latter inclining each way, in such a manner as to form a trussed tube The object of the trusses is not to aid in supporting the load, but to prevent excessive undulation.

The upper floor is secured to the upper cables by means of wire rope suspenders, and it carries the railroad track.

The lower floor is in the same manner secured to the lower cable, and forms the foot and carriage way.

The structure is secured against lateral vibrations by means of wire rope guys from each side of the lower floor to rocks on each bank of the river.

Construction of Parts.

I. *Cables.*—Each cable is composed of 3 640 iron wires, scant No. 9 (Birmingham gauge), first laid in seven separate strands or bundles of straight wire made continuous by splicing. They formed a loop at each end which rested in a groove around the outside of a cast iron U-shaped shoe. Each strand was built with a much less deflection than what the cables now have in order to facilitate their adjustment, and when each was completed it was lowered into place, and fastened to the anchor-bars, as will be described under head of anchorage. After the seven strands were completed and adjusted, they were served closely with wire throughout their length, with the exceptions of those portions on the top of the towers, and about 13 feet of their length at each end, thus forming one cylindrical bundle 10¼ inches in diameter.

II. *Anchorage.*—The dotted curved lines in Figure 1, Plate XXIV, show the profiles of the chains from the ends of the cable to where they enter the rock. The stone supports under each joint of the chain are shown in their respective positions in the wall enclosing the chains.

The plan and elevation, Figure 2, Plate XXIV, show the method of securing the ends of the cables to the ends of the chains. The three shoes (*a*) alternate with four bars, and the four shoes (*b*) alternate with five bars, and are secured by pins passing through heads of bars and openings of shoes. The other ends of all the nine links are secured to the next length of chain by one pin passing through all the heads.

Pits were sunken into the rock to a depth of 25 feet, their dimensions in plan being 3 feet x 7 feet. At the bottom they were enlarged to 7 feet square for the reception of heavy cast-iron anchor plates. The chains entered the rock vertically, and passed downward to the plate where the lower end of each bottom link passed through a separate hole cored through the plate, and was secured by a pin passed through the heads of the links, and resting in concave seats in the lower edges of the partitions. The plates and chains were then built in solidly with blocks of stone cut to fit each place, and thoroughly grouted so as to exclude water from the iron.

The portions of the chains and of the strands to a point 10 inches above bands (*d*), Figure I, Plate XXIV, were covered by masonry, and all the interstices grouted.

III. *Arrangement of Top of Tower.*—On top of the tower is a heavy iron plate bedded in cement and covering the surface 8 feet square.

The upper surface of the plate has three ribs cast upon it parallel to the line of the cables. The two clear spaces between these ribs are each 2 feet wide, and the surfaces of the plates are planed. Each groove has a set of turned iron rollers 5 inches diameter, lying close together, and at right angles to the ribs. Each set of rollers supports a cast-iron saddle, whose underside is planed to rest on the rollers. The upper side of the saddle has a groove of semi-circular section in which the cable lies.

The spaces among the wires at the saddles, at the shoes and all the length of the cables, were flushed with Spanish brown paint to keep out moisture.

IV. *Old Suspended Superstructure.*—The construction of the old work will be described under head of ***Renewal of Suspended Superstructure.***

Inspection.

In February, 1877, Mr. Thomas C. Clarke, Member A. S. C. E., visited the bridge and caused an excavation to be made in the masonry covering the strands of the Canadian end of the lower north cable. On reaching the strands near the shoes, two or three of the outside wires were found to be corroded quite through, and a number of others were more or less corroded, and presented an appearance that was not very encouraging. In view of the possible extent that the deterioration might have reached, it was deemed best to reduce the weight of the trains crossing the bridge until a more thorough examination could be made.

Shortly afterward, Col. W. H. Paine, Member A. S. C. E., of the East River Bridge, went to Niagara, and proceeded to make a thorough examination. Men were set to work removing all the masonry from the strands and the first lengths of the chains. With a vernier scale he measured the elongation of the strands produced by a load on the bridge. He cut out some of the wires and tested them, both in tension and by bending them over the corner of a pair of sharp plyers.

Results of Tests.

1st. The elongation of the strains under a given load was found to be what the modulus of the wire would give if the section was full. Showing that the corrosion had not reduced the section of the strands so much as would be allowable, without weakening the cable as a whole, for the reason that the stress at the top of the tower exceeded that at the strands by about the strength of 40 wires.

2d. The results of the tensive tests were satisfactory, considering the fact that the specimens were more or less etched in places. Thus, while they showed an ultimate strength of about the same as the new wire was required to possess, the fracture was fine, perfectly fibrous, and the reduction good, yet the stretch was confined principally to the etched portion, where the specimen broke. This rendered a proper measurement difficult, inasmuch as the portion observed was several inches in length, while the part stretched would not exceed one-half inch.

It was interesting to note that even where a wire had its section nearly half eaten away, its ultimate strength would still be from two-thirds to three-fourths that of a whole wire, showing that the weaker portion of the metal were attacked first.

Repair of Wires.

On the 16th of March, 1877, the writer joined Col. Paine at Suspension Bridge to assist in examining the bridge and in repairing the defective wires.

After the strands were perfectly cleaned and the wire bands were removed, they were opened, and the inner wires were examined as far as it was possible to get at them, when they were found to be as clean and smooth as when first put in. After cutting out the defective portions of the outer wires, the next layer of wires, thus uncovered, where they bend around the shoe, were found to be clean and bright, proving that the only wires affected were the outer wires of the outside strands.

Near the band, which confined all the strands into one compact bundle, the outer wires were found to be slightly etched entirely around the cable. From that point toward the shoes the etching of the outer wires on the upper side decreased, while underneath it increased, till at the shoes the etching was mostly underneath. The evident cause of the corrosion was the elongation and contraction of the wires of the strands, due to loads passing upon and off from the bridge, thereby loosening the wires from the cement, thus admitting moisture, which gradually worked down to the lowest point. The portion of the cement among the strands would go and come with the strands themselves, thus excluding the moisture. Occasionally a lime stone spawl had been carelessly permitted to come into contact with the wires, when they were being covered, in which case it had caused a black spot, which, on being scraped, would reveal the outer wires corroded partly through.

While the examination was going on, the defective wires were cut out and new pieces were spliced in under a strain equal to that on the other wires.

The method of splicing in the new wires was as follows:

1st. The wire bands were removed from the strands and that portion of each wire, seriously corroded, was cut out. Each of the remaining ends were filed to a scarf and the side opposite the scarf, nicked with a set having transverse grooves across one end.

2d. A piece of new wire, a little longer than the piece removed, having one of its ends scarfed and nicked as above described, was spliced to one of the fixed ends by clamping the scarfs tightly with a small hand vice and then beginning at the middle of the splice it was served closely each way, to a point about one inch beyond the splice, with No. 20

annealed iron wire and fastened there by giving the wrapping wire a couple of "half hitches."

3d. A straining apparatus consisted of two pieces of iron (each about 3 feet long) hinged together at one end. The other ends were each provided with a hook and steel button, for the purpose of gripping the wire. About six inches from the button ends, a rod, with a thread cut nearly its whole length and a nut fitted to it, was arranged so as to draw the two ends towards each other. The new wire was then drawn as closely as possible by hand and one end of the strainer secured to it. The other end of the strainer was secured to the end of the old wire. Then by screwing on the nut the desired strain was applied and the new wire cut to the proper length. It was then released from the strainer and its end scarfed and nicked. The strainer was again applied and, when strained properly, the splice was completed by wrapping as before.

4th. The strain was measured by means of a spring balance. The balance was hitched to one of the sound wires at the middle point of that portion of the wire having no bands. Then pulling on the balance, the wire was deflected from a right line about 1¼ inches—the deflection of wire and strain indicated by the balance, being carefully noted, to be used as the standard for straining all the wires on that strand. When the strainer had strained the new wire to that extent, that with the same deflection, the balance read the same as before, it was then drawn enough further to make allowance for the slip of the splice.

After having completed the splice the strainer was removed and the strain tested by the balance. By exercising due care in making the splice in this manner, it has about the same strength as the weakest point of the whole wire.

The greatest number of wires thus renewed at either end of any one cable was sixty-five. As many of these were but slightly affected, it is not probable that any injury would have been done had the defective wires not been replaced.

In all cases where a wire was cut out, it immediately took the form of an arc of a circle with a diameter of about four feet. As this was the diameter of the coil previous to its going into the cable it was evident that the wires had never been injuriously strained.

Appointment of a Commission to Inspect the Bridge.

The Great Western Railway Company called for the appointment of a commission of engineers to inspect the condition of the bridge, according to the terms of their contract in leasing the railway floor.

The Bridge Directors selected Col. W. H. Paine, the Great Western chose Mr. T. C. Clarke, and these two gentlemen agreed upon Mr. Charles Macdonald (all members of the Am. Soc. Civ. Engr's) to complete the commission.

They arrived at the bridge April 17th. During that and the three following days, they made a very thorough examination of the cable strands and also of those portions of the chains that were accessible. Very close attention was given to the condition of the chains. Measurements were taken of the sections of all the upper links of each chain to ascertain the amount of metal in the bodies of the bars and of the heads each side of the pin, discovering the following conditions:

1st. The outer bars of each set had a rather greater section than any of the intermediate ones, and the total section of the bodies of the nine links of a chain was 86.625 square inches, the average width of each bar being 7 inches and the thicknes $1\frac{3}{8}$ inches.

2d. The diameter of the pin was slightly under $3\frac{1}{2}$ inches, or hardly five-tenths the width of the body of the bar. The form of the head was approximately circular with a diameter of about 12 inches. The centre of the pin-hole, was in some instances so far toward the body of the bar from the centre of the head, as to leave the minimum section on each side of the eye less than half that of the body of the bar.

3d. Nearly all the pins in the shoes were found to be bent convex toward the cables, in some cases the convexity amounted to $\frac{5}{16}$ in. in the total bearing length.

Before leaving the bridge the Commission caused a train consisting of a switch engine and 20 loaded box cars, weighing 450 tons, to be run upon the bridge and had the curves of deflection taken for each position of the train in which the centre of gravity of the engine was at points 100 feet apart. (See plate XXIX, Fig. 1).

After due consideration the Commission reported substantially as follows:

The action of the wire portion of the cables, together with the results of tests of pieces of wire, indicate that when the work of mending the defective wires is completed the cables will be in good condition.

Regarding the anchor chains it was believed that the form of heads and size of pins were such that they would not withstand a strain greater than would be produced by 40 000 pounds per square inch of transverse section of the body of the link. Consequently while each cable was composed of 3 640 wires, each wire possessing an ultimate strength of 1 648 pounds, giving to it a total ultimate strength of (in round numbers) 6 000 000 pounds, the chain would not possess a greater ultimate strength than $86.625 \times 40\,000 = 3\,465\,000$ pounds, or 2 535 000 pounds less than that of the cable. Hence if the chain was reinforced sufficiently to make it equal the cable in strength, it would require an increase of section (estimated at 50 000 pounds per square inch) of 50 square inches area.

The report was accompanied with plans for this re-enforcement, and required that it should be made. It also suggested the renewal of the truss system, and submitted a general plan for an iron structure to replace the old wooden one.

Re-enforcement of Anchorage.

The writer, who was selected as engineer to execute the work of re-enforcement, arrived at Suspension Bridge September 13, 1877, with authority to make such alterations in the plans as circumstances might necessitate.

The data upon which the Commission's plan was prepared, aside from that ascertained by the inspection, were taken from the plates accompanying Mr. John A. Roebling's published report on Niagara Bridge. The plan was as follows:

1st. Four pits were to be sunk in the rock, one at the back end of each anchor wall. From each one of these pits two pairs of chains were to pass up to the surface of the rock from anchor plates secured at the bottom. From the surface of the rock the two middle chains were to pass in a vertical curve to a point at which the curve became tangent to the line of the upper cable and thence to the shoes, one on each side.

2d. Each shoe was to have a cast-iron block fitted in its opening, with one end concave, to fit against the pin. The other ends of all the blocks of a set were to project slightly beyond the forward ends of the shoes and have their ends faced in one plane at right angles to the centre line

of the cable at its intersection with the plane. Against these blocks were to rest the planed surfaces of two cross-bars. The ends of these bars were to project far enough at each side, and be rounded, to receive the ends of the two chains.

3d. The other two chains were to pass one on each side of the old wall, and in a vertical curve, till they were tangent to the line of the lower cable, and thence directly to the ends of cross bars arranged the same as those in the upper cable.

4th. The chains were to be of such length that when their ends were secured, as above described, one joint, *A*, of each, on the curved portion, should be a couple of inches nearer the centre of the curve than any of the other joints.

5th. After the chains were all in position, heat was to be applied to the chains to expand them sufficiently to allow of raising the low joints and blocking them with iron plates to such a height as would produce the proper stress upon the chains when cold.

6th. To measure the stress upon the chains, each of the bars forming the upper lengths of the chains was to be subjected, in a testing machine, to a tensive stress equal to the permanent stress it was to have when in position. The elongations corresponding to each bar, while under this stress, were to be carefully noted, and they were to be strained when in the work till they had the same elongation.

Changes of the Plan.

After uncovering the rock for the purpose of sinking the anchor pits, it was found that the old walls extended back further than was shown in the plates of Mr. Roebling's report, and that the line of the lower cable, produced, would enter the rock at a point nearly 30 feet from the new pit on the New York side and 12 feet on the Canada side. This would necessitate very expensive trenches, the excavation of which would be liable to disturb the old walls and perhaps the old anchorage of the upper cables.

To obviate this difficulty, the alteration was made, a description of which will be assisted by reference to Fig. 1, Plate XXIV. In this the pits were located the same as before, but were to be smaller. All the four chains in one pit were secured to a single anchor plate, by one pin, also by one pin in the first joint *C*. Beyond *C* each of the four chains was

independent of the others, but had the same curvature and rested on the same stone supports, to the point of tangency with the line of the upper cable, from which point two of the chains went to that cable. The other two passed, one on each side of the old upper cable chains and supports, in grooves cut in the masonry, and were secured to the lower cable. This arrangement required a bend in the chains to bring them on to the line of the lower cable. The consequent upward component of the stress was opposed by three pairs of stirrups attached to the projecting ends of three pins of the old chain, as shown at *a*, *b* and *c*.

The connection with the strands is made as by the Commission's plan, except that instead of the last links connecting directly with the cross-bars, a triangular link is interposed as shown by the dotted line in Fig. 2. The arrangement of the holes in this link is shown in Fig. 3. Its object is to cause a proper distribution of the stresses. There being three strands above and four below, the resultant of stress upon the entire chain was made to coincide with the centre line of the cable at this point, and to intersect, at a right angle, the line joining the points *e* and *f*, the centres of the cross-bars, at a distance from *e* equal to $\frac{4}{7}$ *ef*, while the centre of the pin connecting chain and link is at *d* on the centre line.

Application and Measurement of Stress.

These were made as before described in the case of the upper cable; but in that of the lower it was not necessary to apply heat, as the joint *A* could first be raised and blocked, after which the stress was applied by screwing down the nuts of the stirrups at *a*, *b* and *c*, until the scale indicated the proper elongation of the links.

The total sectional area of new chains for each cable is 50 square inches for that part from the strands to the upper point of curvature. From the latter point downward it diminishes till, at the anchor plate, it is 40 square inches.

The permanent stress upon the chain, or that from dead load alone, is 8 000 pounds per square inch.

The cross-bars are of crucible steel, of a pretty high grade, but thoroughly annealed. They are never subject to any shock.

Method of Doing the Work.

1st. *Sinking the Pits.*—In plan, the pits are 6 feet by 2 feet 6 inches.

On the New York side they were sunk to the depth of 17 feet; on the Canada side, to 23 feet. At the bottom they were chambered to 6 feet by 7 feet in plan, for the reception of anchor plates.

In sinking the pits, holes were first drilled along the four sides of each pit, as near together as was possible without having the drill break through the partition, and to nearly the designed depth of the pit. The core was then blasted out with light charges of dynamite, that being more local in its effect than gunpowder, and being less troublesome to use under water, of which we had an abundance, especially on the New York side.

The roofs of the chambers at the bottom of the pits were dressed and bush hammered to plane surfaces, sloping outward and downward, each way from the shaft. Just above the chambers notches were cut into the sides and ends of the pit (see Plate XXIV, Fig. 1).

2d. *Anchor Plates.*—These are of cast-iron, 5 feet 6 inches square, and strongly ribbed. Each plate has eight cavities cored into it, for the reception of the lower heads of the bottom links, enclosing them perfectly. One pin passes through all the eight links and all the partitions of the plate. The upper surface slopes outward and downward each way from the four sides of the rectangle occupied by the link openings. After the plate was placed in its proper position in the chamber it was solidly concreted underneath.

The stone blocks above the plate were cut to fit each place, as large as could be got in, and with thin joints. All vacant spaces were filled solidly with stone blocks set in cement, but no stone was permitted to come into contact with the links.

The shafts of the pits were not filled entirely until the stress was adjusted upon the chains.

2d. *Taking Down the Old Walls.*—In removing the portion of the old wall preparatory to placing the chains, they were taken down nearly to the position of beds of the knuckle supports, and then the remaining portion was cut away with points and bush hammer to insure thin joints and solid beds.

The work of cutting the grooves, each side of the wall, for the reception of the lower cable chains, required extreme caution, especially where they passed alongside of and under the ends of the stone supports of the old chains. In the case of the south wall, on both sides of the river, these

old supports had been solidly bedded, but in both north walls we found large cavities under some of the supports. In such cases we were compelled to suspend cutting till the cavities could be solidly filled with cement mortar, and allowed to set, as of course the least settlement of any of these supports would destroy the adjustment of the cable, if it did not endanger the bridge.

After the new chains were adjusted the masonry was rebuilt, and both new and old chains covered and grouted solidly. But the wire strands are covered with brick houses properly supplied with means for drainage and ventilation. The roofs of the houses are provided with hatchways, the covers of which can readily be removed for purposes of inspection and painting.

Durability of the Work.

Referring to Fig. 1, Plate XXIV, it will be seen that the only manner in which the new chains can become slackened is from the settlement of the knuckle supports, and shrinkage of the joints around the anchor plates.

The portion of the old walls on which the new supports were placed was very firm, and, as the joints were all thin and the stones well bedded, there can be no danger of such settlement.

At the time the stress was applied the weather was warm, and the sun shining upon the chains, keeping them warmer than they can be again, covered with masonry as they now are. Hence the stress must have increased somewhat by covering them.

Again, one of the chains was left uncovered from D to F for two weeks, and the joint at E unsupported; yet the joint only deflected half an inch out of the right line from D to F.

In concluding this account of the anchorage, it is proper to speak of the developments made in uncovering the old chains.

The curved portions of all the chains had settled forward toward the river and downward, leaving cavities between the cement and upper edges of the links and back of the pin ends. The cavities were largest at the upper joint, and nearly disappeared about the third joint down. The portion of the metal thus exposed had a thin coating of rust. On chipping off the cement forward of the pin ends, and at the sides of the links, the Spanish brown paint came off with the cement, and left the surface perfectly bright. This condition indicated that the masonry

covering of the chains had been put on before the weight of the bridge and cables had been applied.

The outside links of each set being slightly heavier than the intermediate ones, while they should have had but half the sectional area, would naturally elongate less under stress than the intermediate ones, and thus account for the bending of the pins before mentioned.

The pin holes of two of the outside links, which were accessible, were elongated, so as to leave an opening behind the pin of about $\frac{1}{8}$ inch. On this account I feared that some of the intermediate links might be in worse condition, but fortunately two adjacent heads of intermediate links were separated about $\frac{1}{4}$ inch, and by bending the sharpened point of a small wire, and inserting it, I could have felt the cavity, had there been one, but found no place large enough to receive the point. Hence I concluded that the other pin holes had been bored larger than they should have been, or that the bar had been short, and the eye filed or bored elliptical.

The removal of the masonry covering the old chains exposed all that portion of them about which there should be any doubt regarding their proper preservation, as the nearer we approach the anchor plates the less is the movement due to elongation produced by live loads, and the exposed links were carefully scraped and painted before re-covering them.

Renewal of the Suspended Superstructure.

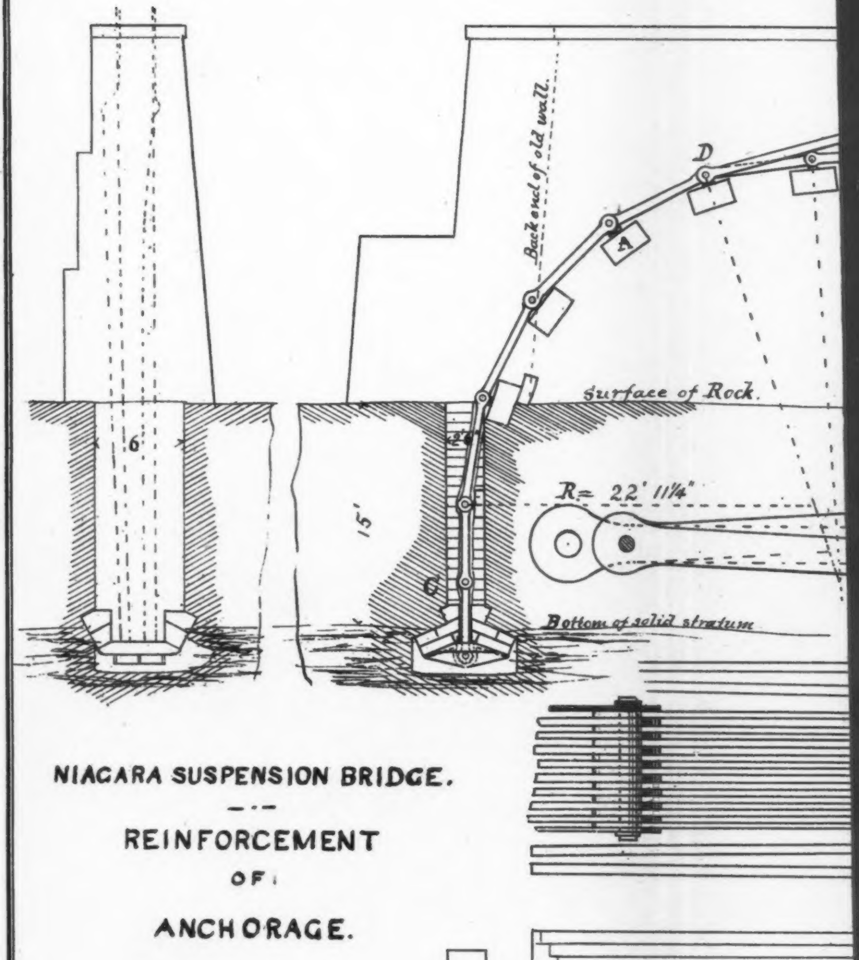
During the progress of the work on the anchorage, the writer made a careful examination of the suspended superstructure, both for the purpose of ascertaining its condition and to enable him to prepare some plan of either repairing it or of entirely renewing it with wood or iron.

The following in connection with Plate XXVII is a description of the suspended superstructure :

1st. *A Series of Transverse Bents.*—There was one bent at each five feet in the length of the bridge, or 161 bents in all. Each bent consisted of the following members :

a. Upper Floor Beams.—Each beam consisted of two pieces of 4 inches by 16 inches pine timber set on edge parallel, and 6 inches apart. These beams were 25 feet long.

b. Lower Floor Beams.—Each lower floor beam consisted of two pieces of 4 inches by 16 inches pine, 19 feet long, and two pieces of 6 inches by 13 inches pine, each 12 feet long. The 4 inches by 16 inches



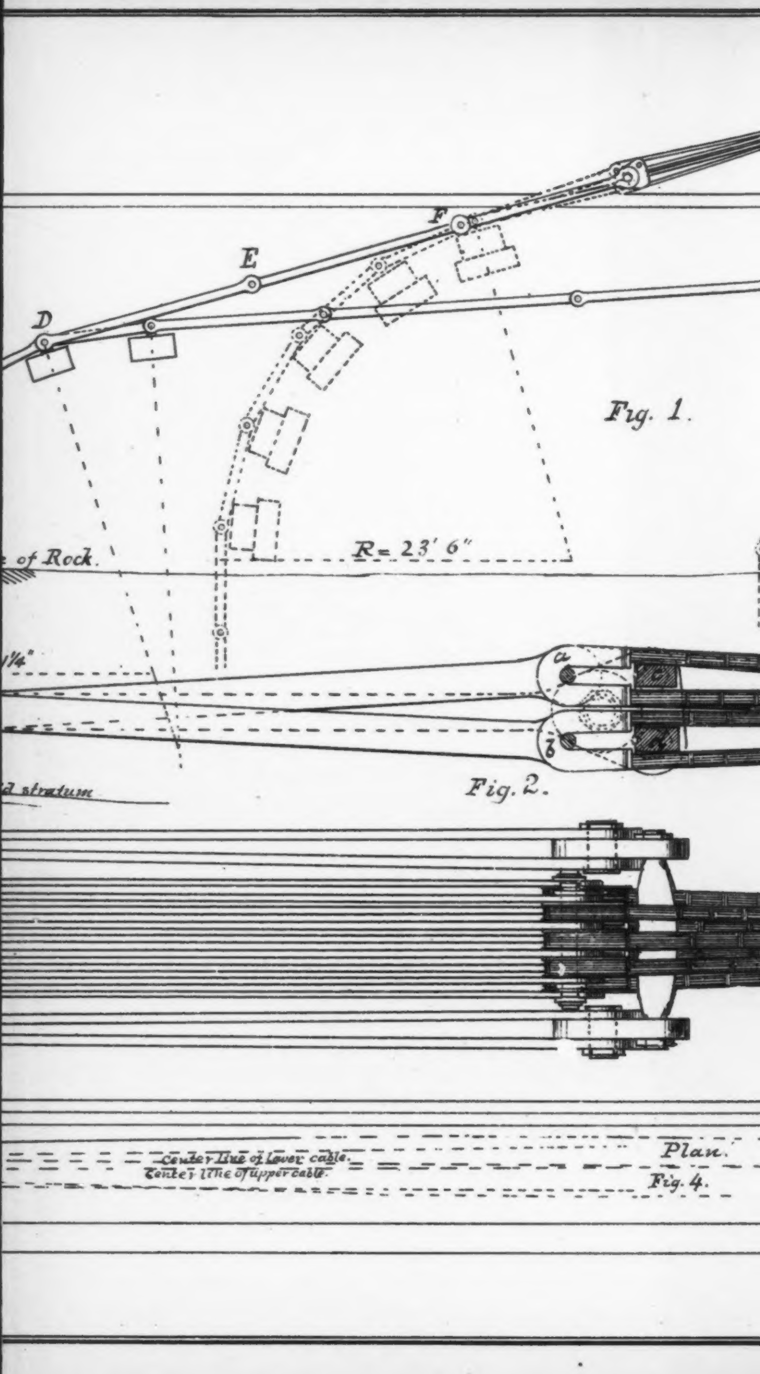
NIAGARA SUSPENSION BRIDGE.

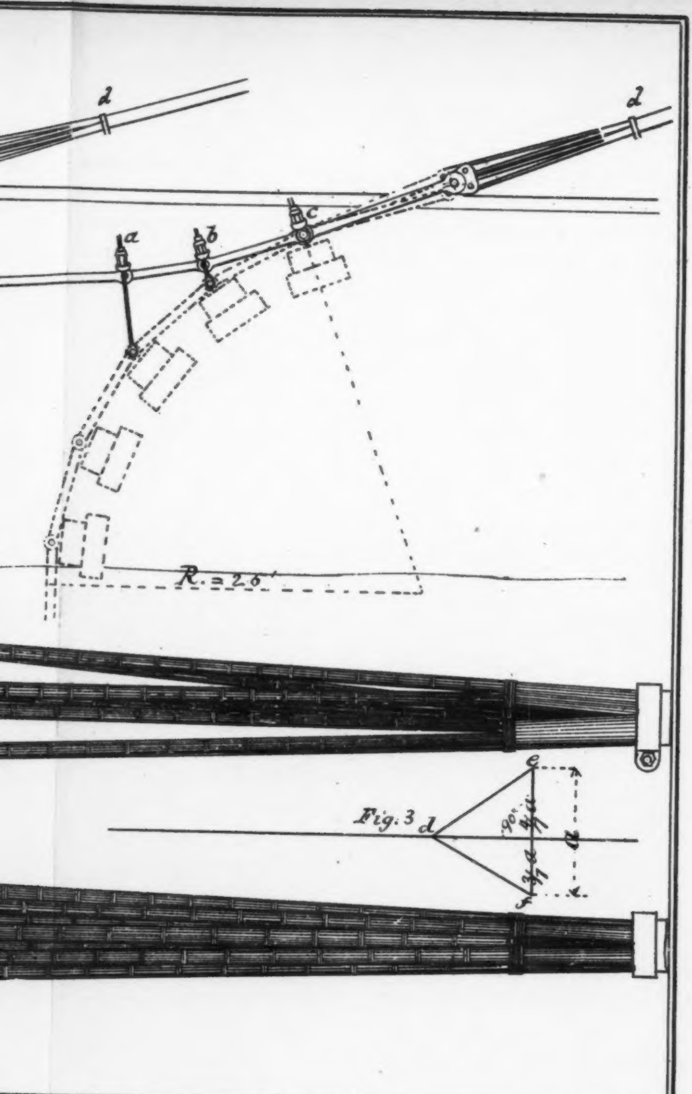
REINFORCEMENT

OF

ANCHORAGE.

PLATE XXIV
TRANS. AM. SOC. CIV. ENG'R'S
VOL X Nº CCXXIII
BUCK ON NIAGARA BRIDGE


D
E
F
Fig. 1.
of Rock.
R= 23' 6"
1¼"
a
b
Fig. 2.
d stratum
Center line of lower cable.
Center line of upper cable.
Plan.
Fig. 4.



d
d
a
b
c
R. = 26'
Fig. 3
d
e
f
90°
a

pieces were set on edge, and the two pieces of 6 inches by 13 inches were placed between them, with their ends abutting at the middle of the first two. They were strongly bolted together.

c. Posts.—There were two wooden posts, with a clear space between of 19 feet. Each post consisted of two pieces of 4 inches by 16 inches pine, separated by 4½ inches packing blocks. The upper ends of the posts were clamped between the two parts of the upper floor beam, and the tops flush with the upper edge of the beams. The feet of the posts rested on top of the 6 inches by 13 inches pieces of the lower beam, and were kept in place by white oak shoulder blocks spiked to beam and post on each side.

d. Knee Braces.—There was one knee brace of wood and one of iron from each post to the upper beam, and and one of iron from each post to the lower floor. The upper wooden brace from the inner face of the post, and the iron one from the outside. The lower brace was from the inner face of the post to the floor.

2d. *Longitudinal members.*

a. Chords.—The upper chords were composed of two thicknesses of 2 inches by 12 inches white oak plank, one thickness in length of 5 feet, with the joints midway between the floor beams and resting at its middle portion on top of the floor beam and end of the post, while the other pieces were just long enough to go in between the floor beams and serve as a splice for the joint of the other piece. The two thicknesses were bolted together with eight one-half inch bolts to each panel. A double cast-iron angle washer for the end of the truss rod, was let into the top of the chord over each plate.

The lower chords were constructed in a similar manner, except that there was a 4 inches by 12 inches thickness of pine resting against the under side of the floor beam, then a 2 inches by 12 inches oak plank under this. On top, between the beams, was a 2½ inches by 12 inches pine plank. These were were bolted together with eight ½-inch diameter bolts, and had a double angle washer let into the under side, below each beam. This, together with the lower floor, was all the lower chord the bridge had at first, but as it was soon found to be insufficient, auxiliary chords, composed each, of two lines of timber were bolted to the under sides of the floor beams, and with a two inches space between it and the inner edge of the first lower chord. These timber chords were made continuous by scarfed and keyed splices, and were keyed to each other

at intervals of 2 feet 6 inches, with the splice of one at the middle of the length of the other. One of the timbers was 10 inches by 12 inches, and the other 10 inches by 8 inches. The stresses were transmitted to this chord by the transverse stiffness of the floor beams.

b. Track stringers.—There were two deep longitudinal track stringers, built partly above and partly below the upper floor beams. The portion above the beams was composed of 4 inches by 15 inches pine plank piled closely, broad sides horizontal, to a height above the beams of 2 feet 6 inches. The rails of the track were laid directly on the tops of these stringers.

The portion of each of the stringers below the floor beams was composed of two lines of pine timber made continuous by scarfed and keyed splices. That next the beam was 12 inches by 12 inches. The bottom one of 10 inches by 12 inches. The upper and lower portions of the stringers were secured together by four 1 inch diameter bolts passing from top to bottom in each panel.

c. Hand Rails.—Along each outside edge of the upper floor were two heavy hand rails, made on the Howe truss principle, the lower chord of which was under the ends of the upper floor beams.

d. Floor Planking.—The upper floor planking was in one course. That part between the track stringers being 4 inches thick. The remainder 2 inches thick. It was of pine, laid longitudinally with the bridge.

The lower floor was of two 2 inches thicknesses laid longitudinally, the first of pine and the second of oak. These were fastened to the floor beams with heavy wood screws.

e. Cornices.—To the ends of the upper and lower floor beams were secured strong cornices.

f. Truss Rods.—The truss rods of the middle four hundred feet were of 1¼ inches diameter round iron. The remainder were 1 inch in diameter. They formed quadruple triangulation in each direction, passing through the chords and angle washers where they were secured by a nut on each end.

3d.—*Suspenders.* Each bent was suspended to the cables by four 4½ inches circumference wire rope. Those from the lower cables were attached to the projecting ends of the lower floor beams, near the trusses by means of U shaped stirrups.

Those from the upper cables were attached to the upper floor beams,

one on each side, midway between the track and truss, secured to the beam by a screw, and with nut and washer below the beam.

4th. *Stays.*

a. Overflow Stays.—From the top of each tower, where their ends were made fast to the saddle, sixteen wire rope stays extended to various points of the upper and lower floors. The longest reached to a point 250 feet from the towers. They were 4½ inches in circumference.

b. Wind or River Stays.—Attached to each side of the lower floor at intervals of 25 feet for the whole length of the bridge, except 75 feet at each end were wind stays, whose other ends were anchored to large rocks on both sides of the river. There were fifty-six of them in all.

The above was the arrangement of the bridge previous to renewal. The upper floor had been rebuilt in 1873, but without altering the above arrangement.

The total suspended weight between the towers, including cables, stays, and water which the lower floors was so admirably adapted to retain, was but little less than 1 200 tons. The expense of keeping it in repair amounted to an average of about $6 000 per year.

Condition of the Structure.

At the time of examining the structure the old chords had become nearly worthless, to resist tension. Consequently, the floor beams had been compelled to transmit most of the stresses to the auxiliary chords below, and to the track stringers and hand rails above. This had caused the slipping of the joints of floor beams with posts and chords, water had worked in and by freezing had opened the fibre of the wood, causing it to decay very rapidly. The lower floor planking had ruts worn into it, so that it did not drain readily. The planking and tops of the beams had decayed so much as to be incapable of assisting the chords. Consequently, the latter had been broken in three or four places, and patched by bolting on planks.

The upper hand rails had been broken in several places, and the joints of the track stringers had many of them worked loose.

In short, there were very few tight joints in the structure. It had, consequently, become extremely flexible. When one-half of the bridge was loaded, had it not been for the overflow stays at the loaded end helping to sustain the load, and of the river stays at the opposite end helping to balance the load by holding their portion of the bridge down the

trusses would have been of very little use. Consequently, it was evident that any attempt to repair the structure would only result in the rapid destruction of the new work, and the more rapid destruction of the old.

Discussion of the Advisability of Rebuilding the Superstructure in Iron.

1st. It was of primary importance that whatever was done, the traffic over the bridge must not be delayed during the time occupied by making the change.

2d. Whatever material was used it must combine lightness with strength. The traffic over the bridge is continually increasing in weight, rendering it necessary on the one hand to provide a stronger superstructure, and on the other to decrease the weight, so as to increase the factor of safety.

In any bridge where the strain on each member is always in one direction, good sound timber can be made to answer a very good purpose, as when the joints once get settled to a firm bearing, there is afterwards but little movement, and they may, with proper care, be constructed to last a long time. Yet even the timber, suitable for this purpose, is becoming pretty expensive, and not easily obtained at that.

But in the case of a suspension bridge, where the stresses are constantly changing from tension to compression, or *vice versa* it is very difficult to form a wooden joint that will not move more or less. This causes it to wear, and water gets in, which accelerates destruction by softening the timber and causing rot.

Iron and steel is open to none of the above objections. If properly designed and constructed there is no reason why it should not last an indefinite period with proper care in keeping it painted.

Principles to be Observed in Designing such a Structure.

Although the object of the truss is to prevent too great undulation from the action of partial live loads and from wind, yet, to be economical, it must possess a degree of flexibility, for two reasons:

1st. That the cables being anchored at each end to the rock or other fixed material, there is a considerable change of deflection between extremes of temperature, amounting in the Niagara bridge, to about 2 feet.

The truss must consequently bend to accomodate itself to this motion, without subjecting the cables, or its own members, to too great stress in bending it.

2d. The greatest bending moment, to which the truss is liable is when a live load, of maximum intensity per running foot of bridge, beginning at one end, extended two-thirds of the length of the span. Now the greater the flexibility of the truss, the greater will be the deflection of the loaded portion. As the loaded portion deflects the curvature of the cable above it is increased, while the unloaded portion rises and hence the curvature of that portion is decreased. Consequently the dead load of the unloaded segment will balance that of the loaded segment as well as a portion of its live load. This is shown in Fig. 2, Plate XXVIII.

3d. If stays from the tops of the tower to different points of the floors are to be used, the trusses should be continuous from end to end and the middle point of their length should have as little longitudinal motion as possible, in order to make the stays effective at all temperatures. It is to be understood here that the only use of the stays is to assist the trusses. They are of no benefit to the cables.

The first and second of the above conditions are secured, by giving to the trusses such a depth as to allow of the required bending, without straining the metal of which they are made more than the desired maximum. The proper way is to first settle upon the greatest undulation admissible from partial loading, then give to the trusses a depth such that with the given deflection, or undulation, the metal will not be strained above the desired maximum per square inch of sectional area, after which that area must be sufficient to resist the maximum stress.

These undulations do not materially impede the passage of a train.

The third condition is satisfied by providing some automatic device to keep the interval between the ends of the trusses and the abutments as nearly constant as possible.

In the present case the depth of truss was approximately fixed by that of the old structure. But it was somewhat reduced by placing the lower chord on top of the lower floor beams, instead of below them, as in the old structure.

PREPARATION OF PLANS.

While engaged upon the work of re-enforcing the anchorage, I prepared plans for renewing the suspended superstructure in iron.

These plans having received Col. Roebling's approval, it was my wish to let the contract for furnishing the materials, immediately, in order that they might be manufactured and delivered during the fall and winter of 1878-9, ready for erection in the following spring. But the Board of Directors not being ready to commence upon it at that time, nothing further was then done about it.

During the winter of 1878-9 the question of using steel for the suspended superstructure of the East River Bridge came up. I then turned my attention to obtaining what information I could regarding the adaptability of that metal to the Niagara work.

I wish here to express my indebtedness to Col. W. H. Paine for many valuable notes and suggestions, on the use of steel for structural purposes, to the accumulation of which he had given close attention and much time.

There appeared to be no doubt that, for many of the members of the bridge, steel was admirably adapted.

1st. Its great strength admitted of a considerable decrease in weight of structure.

2d. Its modulus being but little greater than that of iron, it will, if given a maximum stress per square inch, proportionate to its strength, afford a given amount of flexibility with, at the same time, a greater depth of truss than could be allowed if iron was used.

This gives a greater moment of resistance to bending with a given chord section.

But the use of steel for structural purposes had not yet reached a stage at which all of the required shapes could be promptly and economically obtained—at least in this country.

Consequently my specifications were prepared to provide for the use of either iron, or steel, or a combination of both materials.

In the month of March, 1879, I was authorized by the Board of Directors of the Niagara Bridge Companies to submit general plans for renewal, to the before mentioned Commission of Engineers. The Commissions written approval was promptly given.

Several bridge manufacturing firms were invited to make tenders for

the contract. May 28, 1879, the bids were opened in the presence of the board and the contract was awarded to the Pittsburgh Bridge Co., of Pittsburgh, Pa.

By the terms of the specifications and contract, the materials were to be delivered at Suspension Bridge, ready for erection, August 1, 1879, and the erection to be completed by November 1, 1879.

The Pittsburgh Bridge Co.'s tender was for Bessemer steel and for iron.

Bessemer steel met the requirements of the specifications very well. The following is an extract of the specifications:

Quality of Materials Required.

Steel.—The steel must be of a quality such that in dimensions to be used it shall have an ultimate tensile strength of not less than 70,000 lbs. per square inch of sectional area, and an elastic limit of not less than 40 000 lbs. per square inch in tension or compression. Specimens bent cold through 90°, with an inner curvature not greater than one and a half diameters of the bar, must not show any cracks or flaws. When the specimens are tested in tension with a strain of 40,000 lbs. per square inch of section, their power for resisting shocks may be tested by striking them smartly with a hammer while under that strain, when they must not crack.

The specimens must elongate at least ten per cent. of their original length before rupture, and the ruptured sections must be reduced at least twenty per cent. of their original sections. Uniformity in modulus and ductility is to be secured as far as possible.

On reaching Pittsburgh, I made some tests of Bessemer steel. They gave very good results. But the only shapes to be obtained, in steel, were plates, angles and small channels. Consequently, the use of steel for the chords would require them to be built up of plates and angles riveted together. This would necessarily reduce the net section to a greater extent than if channels were used. Hence there could be no great advantage, in point of weight, by using steel, unless of a higher quality than that called for by the specifications.

I then found out at what increase of price per pound the steel, made under what was called the "Hay process," could be obtained, whose ultimate strength should not be less than 80 000 lbs. per square inch, and elastic limit of 48 000 lbs. It was then decided to use that material for

the chords, and Bessemer steel for the posts, lateral rods and track stringers. All other parts to be of iron.

The erection of the steel and iron work, and the riveting of their parts together, were included in the contract.

The cutting away to make room for the new work and the removal of the old material was to be done by the Suspension Bridge companies, and the whole work directed by their engineer.

Execution of the Work.

It soon became evident, on account of the unprecedented demand for iron and steel, which arose shortly after the contract was awarded, that it would be impossible to erect the work that fall. However, the work generally went forward in the shops when there was material on hand to enable them to work to advantage.

Every precaution was taken to render the materials and workmanship satisfactory. Tests were made upon specimens cut from every "blow," and then from specimens cut from the actual shapes rolled from each blow, and with no other preparation.

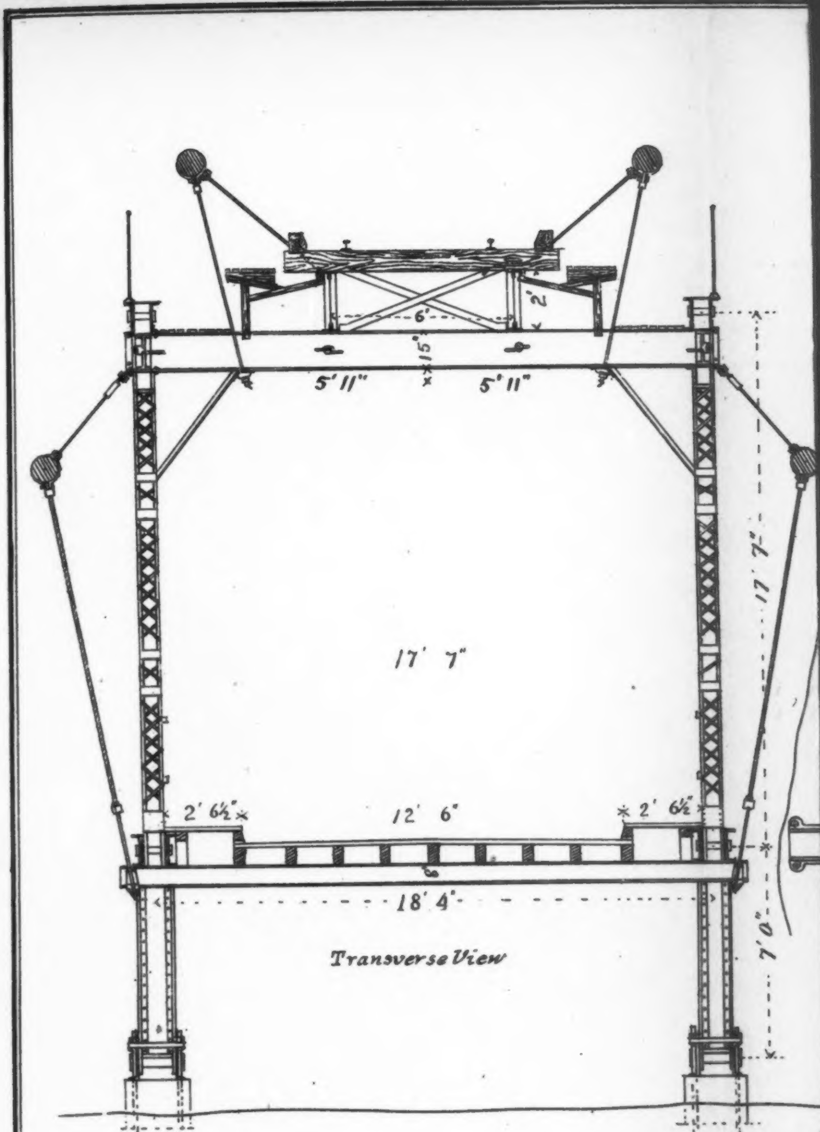
In building the chords, the angles were first punched with a punch about $\frac{1}{8}$ inch smaller than the rivet hole was to be when finished. They were then clamped to the plates in their proper positions, and a drill of proper size passed through both angle and plate, thus reaming the angle, and at same time drilling the plate, with the angle for a templet. Thus the holes were made to coincide exactly.

The rivets were all driven by pressure, steel parts having steel rivets.

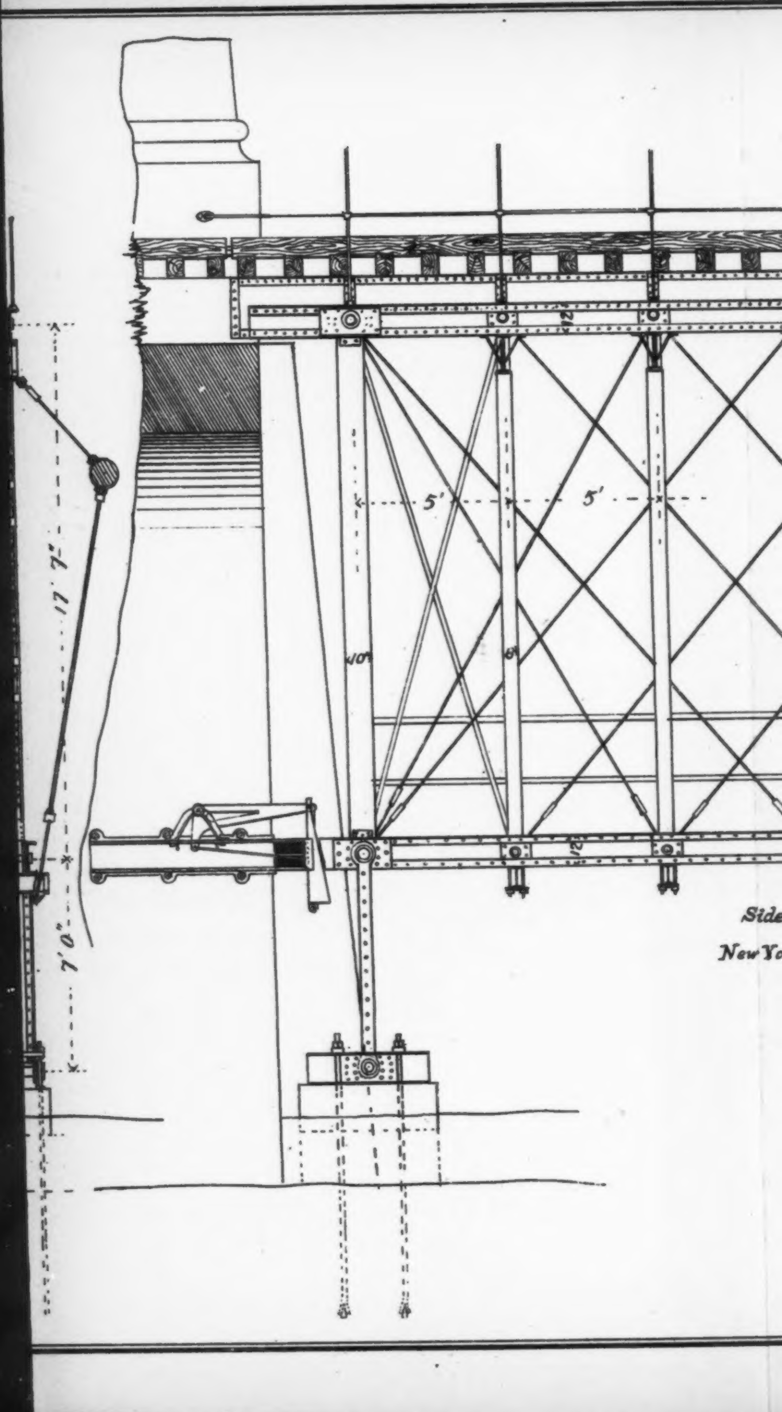
Before commencing the erection, an examination of the lower old floor beams was made to determine whether they would safely bear the increased weight, after having been weakened by the necessary notching, to which they would be subjected in placing the new work. They were found to have deteriorated so extensively that I decided to replace them by the new iron beams before commencing the work of erection proper.

The work of replacing these lower beams commenced April 13, 1880, at the middle of the bridge, and proceeded each way toward the ends. The lower cable suspenders were transferred to the ends of the new beams as rapidly as they were put in place.

As it progressed, the lower floor planking was taken up for a width of about three feet on each side; a temporary wooden railing was put up on each side of the carriage way, leaving, for that purpose, a space nine



Transverse View



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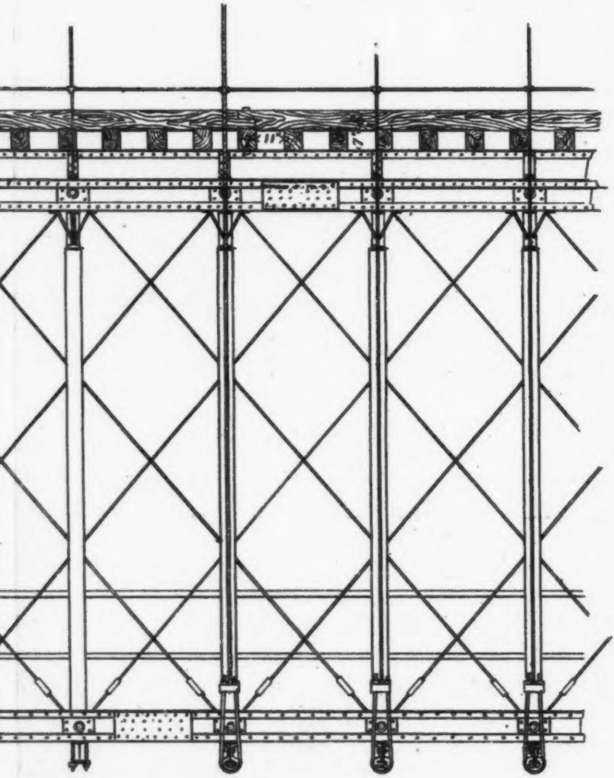

Side Elevation.

ew York End.

NIAGARA SUSPENSION BRIDGE.

Scale ¼ inch = 1 foot.

PLATE XXV.
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feet in width. The cornices above and below were stripped off, the rails forming the Erie broad gauge track were removed, and, in short, all materials not necessary to the stability of the structure were removed, in order to reduce the weight as much as possible. This part of the work was completed May 13, 1880. The weight thus removed was about 80 tons.

ERECTION.

The general arrangement and details of the new work are shown in Plates XXV. and XXVI.

Plate XXVII. shows the position of the new work with respect to the old.

The new superstructure is as wide as would admit of its being placed between the rods of the two old trusses. The bottoms of the new lower floor beams were placed level with those of the old. The tops of the new upper beams were level with the tops of the old, near their ends.

The new upper chords are three inches narrower than the lower ones, to admit of their being put in place without cutting away too much of the old chord.

The outer channel of the lower chord occupied the position of the foot of the inner half of the old post.

The work of erection began May 31, 1880, and proceeded as follows :

1st. Beginning at the middle of the bridge, five lengths of lower chord were placed in position on each side of the lower floor, to make room for which the inner piece of the old post was cut off and blocked to rest on top of the new chord. As the chord lengths were placed, their splices were riveted. The rivets for this purpose are of steel, and from $\frac{3}{4}$ inch to $\frac{7}{8}$ inch diameter. They were driven while hot, with 8 to 10 lb. sledges, which had the effect of upsetting the whole length of the rivet, and making it fill the hole very nearly as well as by pressure.

2d. Beginning at the middle again, one-half of each upper wooden floor beam was cut out. As soon as one of these was taken out, an iron beam was inserted by passing it between the parts of the track stringer, and, when in position, turning it on edge. As soon as an iron beam was in place, a pair of new posts were set up, the lower chord pins passed through chords, posts and truss-rod stubs. The heads of the posts were then placed under the ends of the new beam, and temporarily bolted to its lower flanges. The new beam was then firmly secured between the parts of the old track stringers by means of wooden wedges. The upper

suspenders were transferred to the new upper beams as rapidly as the beams were placed.

3d. As soon as twelve of these new bents were placed, three lengths of upper chord were laid on each side, their splices riveted and their flanges bolted to those of the upper beams.

4th. *New Truss Rods.*—These are in pairs and made adjustable by a sleeve nut with right and left hand threads. They extend from the top of the post to the feet of the third posts each way, forming triple intersection. While the erection was going on, but one rod was put in a place, to avoid overweight.

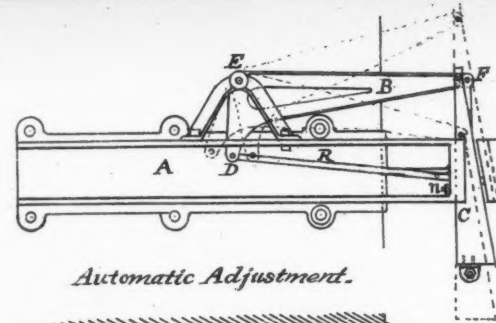
5th. When 150 feet of the new work was in place, the new chords at the end of that 150 feet were secured to the old by means of white oak clamps and keys.

6th. As soon as the clamps were secured, the work of removing the old materials was commenced at the middle of the bridge, and followed that of erecting the new, generally, with an interval of about 75 feet each way. The portion of the new work thus put in weighed about 1 100 pounds per foot run of bridge. Hence, there were seldom over 90 tons of new work overlapping the old. This was equivalent to about 150 tons of distributed load. Deducting the 80 tons saved by stripping the old bridge, we have left 70 tons as the probable extra dead load upon it. But as the trains had at the outset been limited to 190 tons, it is not probable that the total weight of live and dead load ever, materially, exceeded that of ordinary usage. While the above changes were in progress the work of replacing the lower floor planking was going forward each way from the middle.

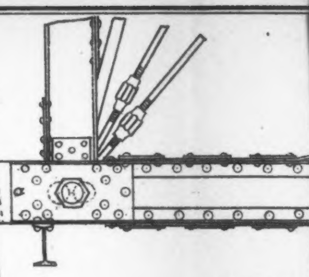
As the old planking was laid lengthwise, while that of the new was laid transversely, there was necessarily a gap between them, which was bridged over by a raised platform, under which the change was made, and which was moved along as the work progressed.

August 25th, all the above work and the riveting of its joints was completed to the ends. Up to that time there had been no interruption of traffic.

7th. *Replacing Track Stringers.*—This began at the middle and proceeded at the rate of 30 feet per day, each way, to the ends. The whole change was completed September 17, 1880.



Automatic Adjustment.



Details

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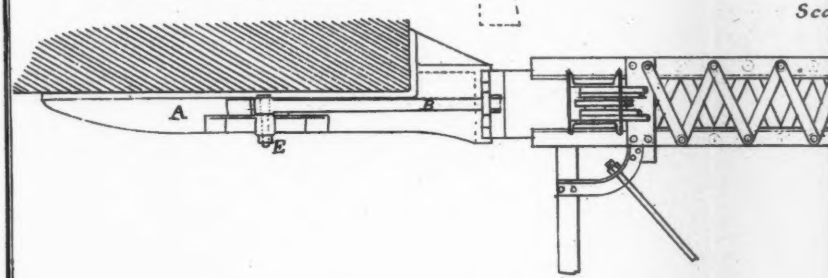
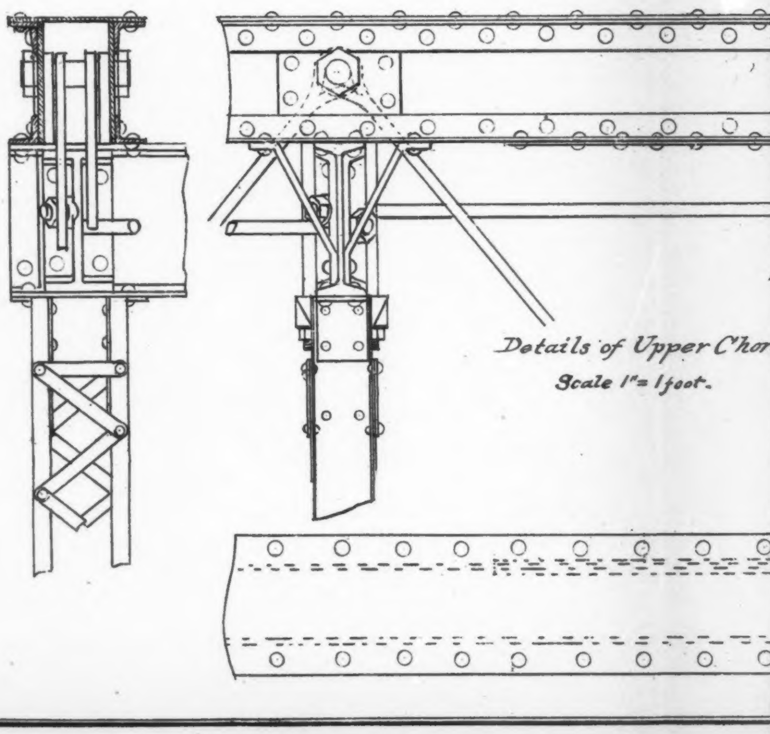
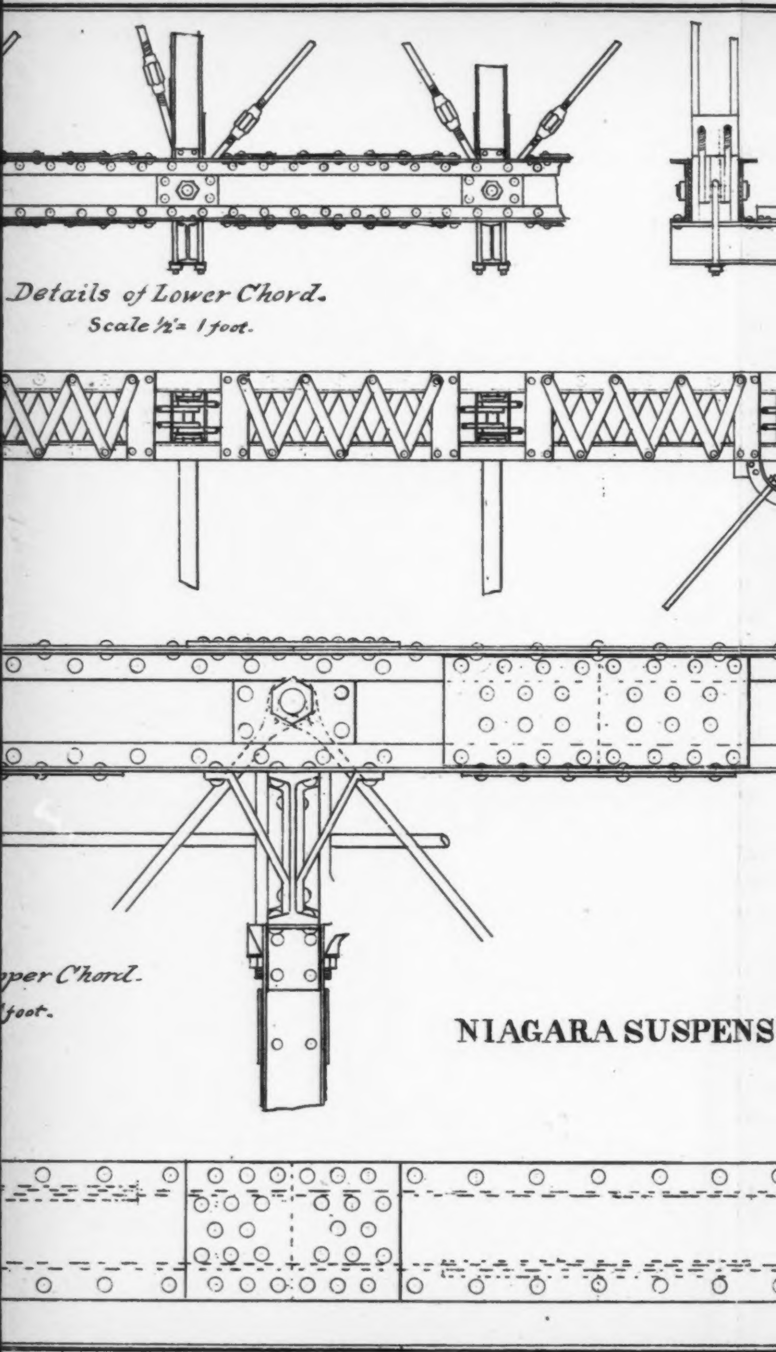
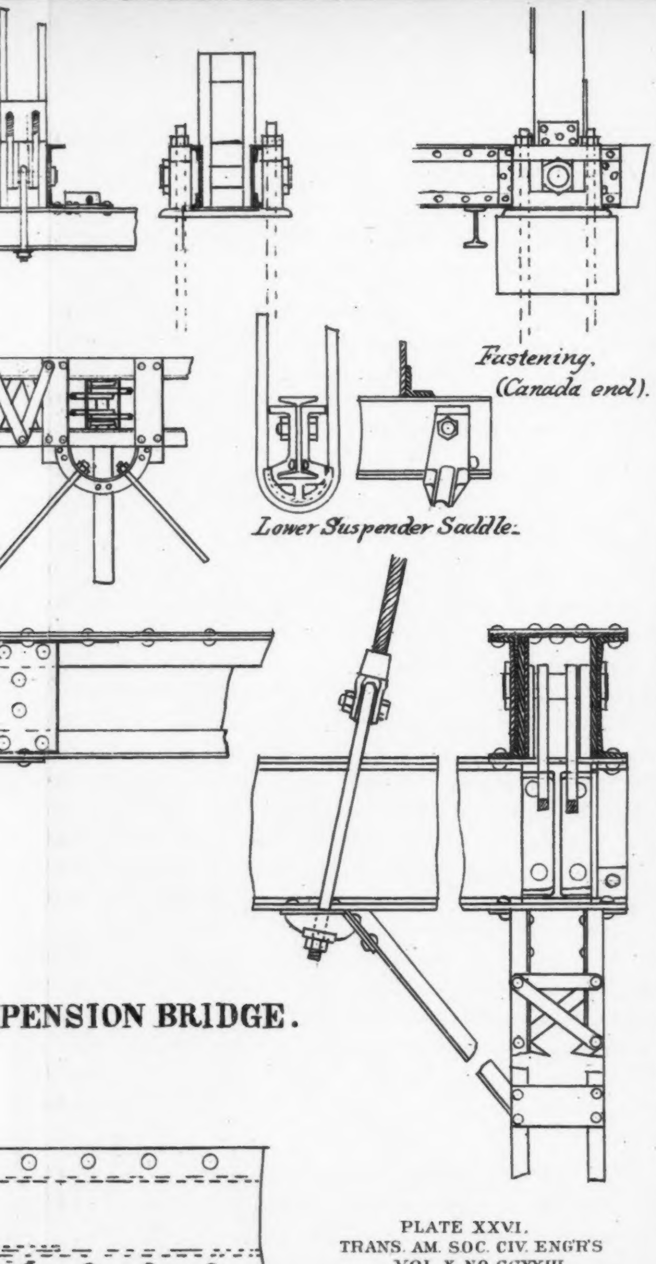




Details of Upper Chor

Scale 1" = 1 foot.


Details of Lower Chord.
Scale ½" = 1 foot.
per Chord.
foot.
NIAGARA SUSPENS



PENSION BRIDGE.

PLATE XXVI.
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ADJUSTMENTS.

The order and manner of making the adjustments were as follows :

1st. *The Camber.*—It was desirable to make the camber as nearly an arc of a circle as possible, at mean temperature. Consequently, the truss rods were all slackened in order to allow the cables to assume their natural curves under the dead load alone. The trusses were then brought to the calculated camber by screwing the suspenders up or down, as the case required. As this raising or lowering progressed, it was necessary to keep the truss rods slackened.

2d. *Stress on Suspenders.*—In making this adjustment, a hydraulic weighing machine was used. The method pursued was to make the machine the connecting link between a suspender and a beam, subject it to the proper stress, as shown by the index, then adjust three or four suspenders on either side of that having the machine attached, and judging of the stress by springing them with the hand, using that actually weighed as a standard. Of course, adjusting the adjacent suspenders would change the standard, which required to be constantly watched and kept to the proper tension. After adjusting all the suspenders in this manner, they were gone over again several times by trying the machine on an occasional suspender, till they were properly strained.

On account of the ends of the trusses being anchored to prevent vertical motion, it was necessary, on nearly approaching the ends, to gradually decrease the stress, till the end suspenders were reached, on which there was no stress.

3d. *Truss Rods*—At mean temperature, with the bridge unloaded, there should be no stress on the truss rods. Consequently, when the thermometer was at about 40° Fahr., the sleeve nuts on the rods were each screwed up to firm bearing, and then turned back one-half of a revolution, thus leaving the rods slack one-sixth of an inch. This gives the trusses a little more flexibility, decreasing the temperature stresses, and at the same time does not allow of more than the proper amount of undulation, as will be seen by an examination of the actual profiles of the floors for various positions of a test load of 357 tons (see Plate XXIX).

4th. *Over Floor Stays.*—The intention being to make the stays assist the trusses, when the live load, beginning at the end, extends about three hundred feet out, a train was moved out to the required position, and while there, the stays were screwed up to the proper stress.

In making the above adjustments, I was assisted by Mr. Frank W. Skinner (of the class of 1879, Cornell University), whom I found to be very faithful to his duties.

Present Arrangement of the Bridge.

The cables, with the exception of the anchorage and ends of the strands, remain as they were. Plates XXV and XXVI show the arrangement of the truss system, but the action of some of the parts will require explanation.

1st. End adjustment.

The object of this is to keep the middle point of the truss system as nearly stationary as possible for all temperatures.

As before stated, this is necessary, in such a suspension bridge as that at Niagara, when it is intended to use inclined stays from the tops of the towers to various points of the floors.

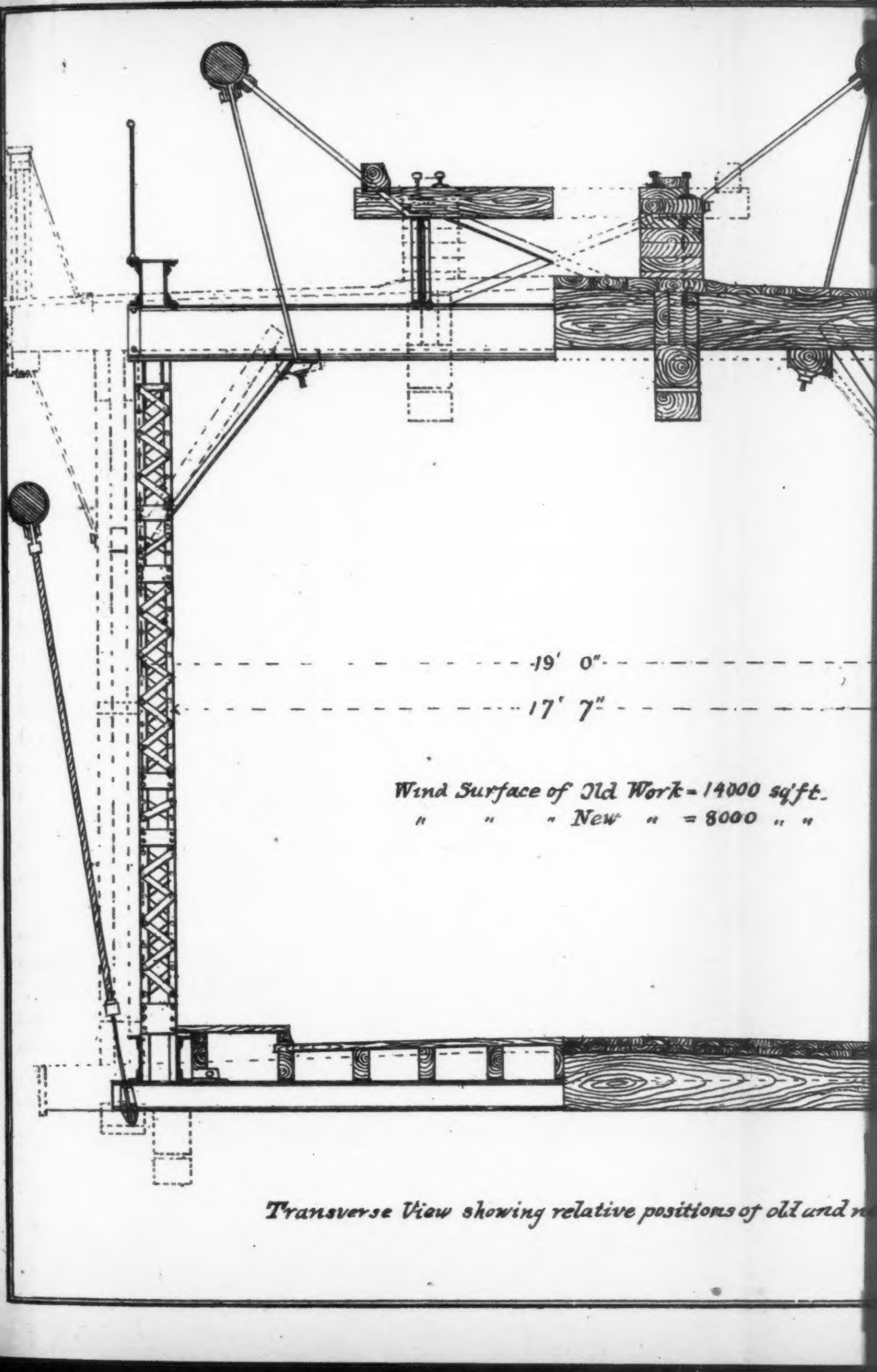
See Fig. 1, Plate XXVIII.

When a wooden truss is used, the point of attachment of the stay to the floor moves in a vertical direction with changes of temperature, further than the change of length of the stay can compensate for. Hence, if the stay is the right length in winter, it will be too short in summer. If an iron truss, with a slip joint in the middle, and ends fast to the towers, is used, the point of attachment will move in a line as *c*, *d*, and is in a worse condition than that where wood is used. But if the iron truss is continuous, and the middle kept from moving longitudinally, the point of attachment of the stay moves in the line *a*, *b*, and very nearly compensates for all temperatures.

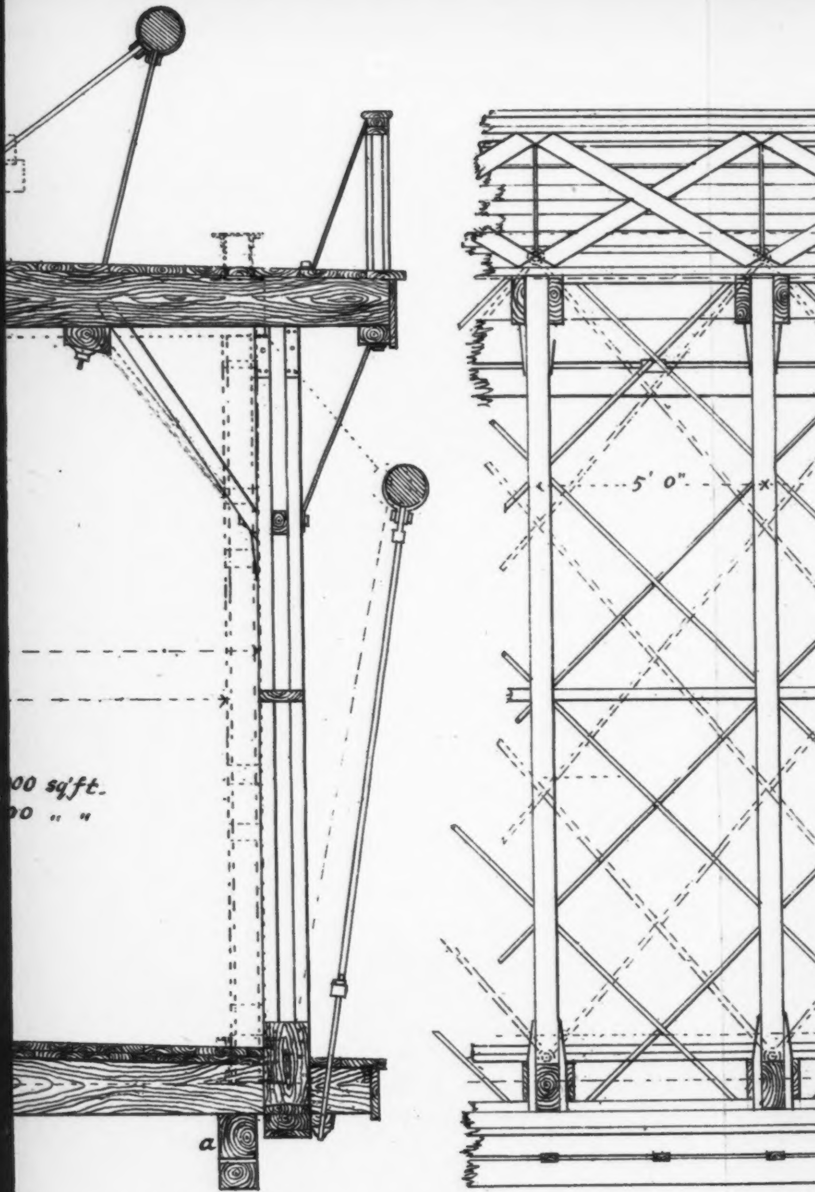
The same figure illustrates graphically the device that was used to keep the middle practically stationary.

The change in length of the truss between extremes of 120 degrees Fahr. temperature is about 8½ inches, or 4¼ inches at each end. See also Plate XXVI.

In each lower chord, extending from end to end of the bridge and lying loosely, are two ⅞-inch iron rods. One end of one rod is fixed to the masonry of the tower, the other end is attached to *D* (Plate XXVI), the short arm of a lever, whose fulcrum is fixed to a casting *A*, firmly secured to the masonry of the tower. The long arm of the lever is three times the length of the short arm, and to its end *F*, is suspended a wedge *C*, having an inclination of 1 to 6 of its length. Then, while the end of



Transverse View showing relative positions of old and ne



of old and new work.

Side Elev

PLATE XXVII.
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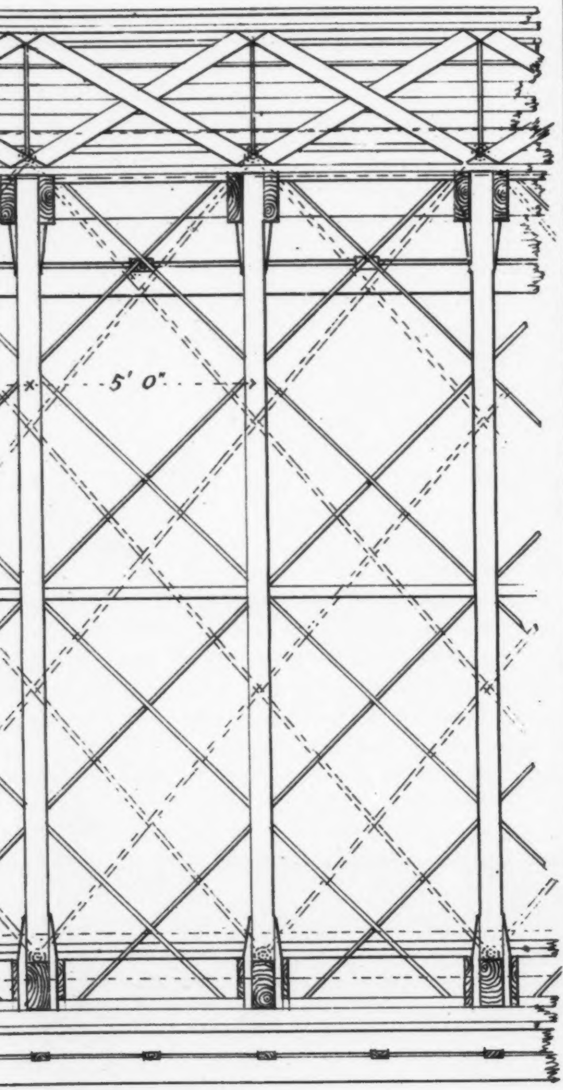


ide Elevation of Old Truss.

the truss moves $4\frac{1}{4}$ inches, the point D of the rod and end of the short arm of the lever moves $8\frac{1}{2}$ inches, and the wedge is consequently moved vertically $25\frac{1}{2}$ inches, or six times as far as the end of the truss moves longitudinally. The rod and chord expand or contract simultaneously, thus bringing a thicker portion of the wedge between the end of the chord and the abutment casting A, as the chord recedes. There is one of these wedges at each end of each lower chord. The wedges do not entirely fill the space between the chord and A, but have about $\frac{3}{8}$ inch of "play" to prevent the wedges from getting caught. This interval of $\frac{3}{8}$ inch is nearly constant for all temperatures. Should the wedges at one end of the bridge get caught at any time, the first engine that passes on to the other end will draw the truss away and release the wedge. The wedges never have caught yet, however, and there is very little liability of their doing so.

2d. *End Fastenings.*—The New York end of the truss is prevented from moving vertically by a hinged strut, Plate XXV. On the Canada end the rock came up too close to the lower chord, consequently, in place of the hinged strut, the end pins of the lower chord are provided with wrought-iron blocks, which are secured in slots of a casting, which allows of the longitudinal motion, but, the casting being anchored to the rock, will not allow vertical motion.

3d. *Upper Floor.*—The deep transverse beams of the upper floor, together with the deep longitudinal stringers distributing the weight over several beams, form a combination that deflects but very little under the weight of a train. Consequently, the knee braces, while they steady the bents transversely, do not spring the posts sidewise, as would be the case were the floor more flexible.

The stringers require to be strong and well spliced, as considerable of the stress that would otherwise come upon the upper chords, is transmitted through the transverse beams to the track stringers.

4th. *Lower Floor.*—The planking of the lower floor is laid transversely to the line of the bridge to allow it to dry off more readily. The narrow foot-walk on each side, not only make clean walks for pedestrians, but they serve to keep snow on the carriage way in winter and confine it to the space only that is necessary for sleighs.

5. *Lateral Stiffness.* As neither floor has any longitudinal planking to stiffen it, diagonal rods were introduced. The 56 wire rope stays are retained to resist the action of high winds, consequently, the only office

of the lateral diagonal rods is to prevent local derangement of the chord lines.

Strength of the Bridge.

The anchorage, cables and towers are the supporting members of the bridge, as before.

The strength of the anchorage has already been discussed.

Cables.

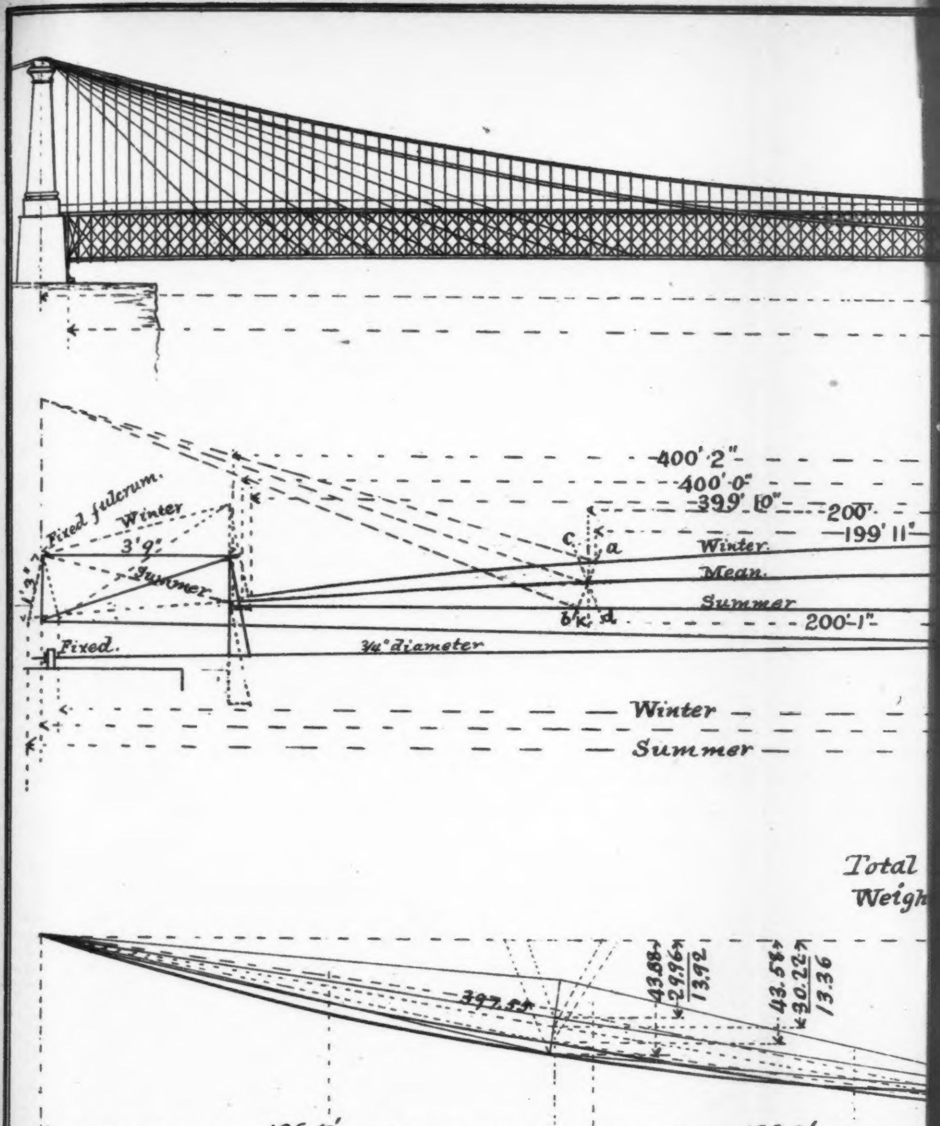
The number of wires in each cable is 3 640. The average ultimate strength of each wire was 1 648 pounds, giving for the strength of one cable 3 000 tons, or for the four cables 12 000 tons, in the direction of their length. There is no indication of deterioration of the wires, but suppose the wires not to have an ultimate strength of more than 1 511 pounds each, that would give for the four cables a strength of 11 000 tons.

The present total suspended weight of the bridge, between the towers, and including the cable, stays, &c., is 1 050 tons. Taking the maximum live load at 350 tons, makes in all 1 400 tons. The greatest stress upon the cables is at the towers, and equals $1400 \times 1.78 = 2492$ tons. Consequently, their factor of safety $= \frac{11\,000}{2\,492} = 4.41$. This is equivalent to a factor of 3 for the dead load and 8.65 for the live load.

Towers.

The maximum load on top of one tower is 700 tons. The section of the tower at the top is $8 \times 8 = 64$ feet. The pressure per square foot = 10.94 tons. The tower has a sufficient batter, so that for any section below the top, the 700 tons + the superincumbent weight of masonry, is less than 10.94 tons per square foot.

But there is one difficulty that must be constantly guarded against, viz.: The stone of which the tower is built is limestone, the surface of which "flakes off" on exposure to the atmosphere, frost, &c., though very strong where it is not exposed. If neglected, this would in time result in the destruction of the towers. It has heretofore been the custom to set new pieces into the faces of the towers when they were required. There appears to be no better method of meeting the difficulty.



400' 2"
400' 0"
399' 10"
200'
199' 11"
Fixed fulcrum.
Winter
3' 9"
Summer
1' 3"
c
a
b
k
d
Winter.
Mean.
Summer
200'-1"
Fixed.
3/4" diameter
Winter
Summer
Total
Weigh
397.5
43.88
29.96
13.92
43.58
30.22
13.36
196.5'
196.5'
393'
0.29
0.30
0.05
0
100'
200'
300'

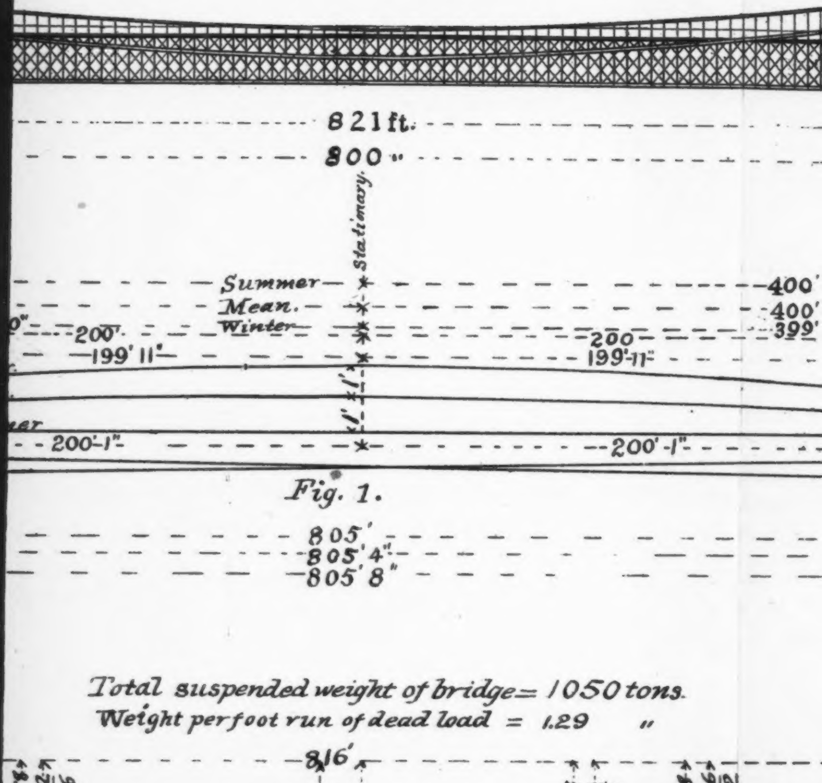


Fig. 1.

Total suspended weight of bridge = 1050 tons.
Weight per foot run of dead load = 1.29 "

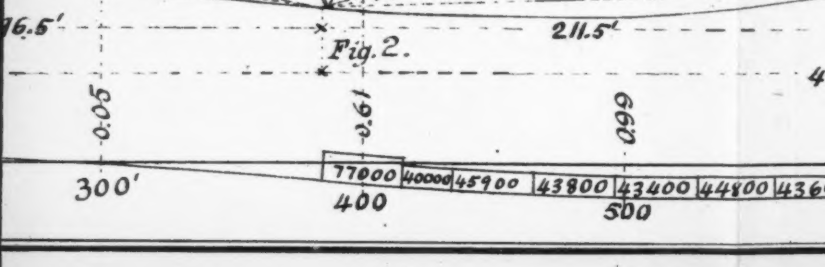


Fig. 2.

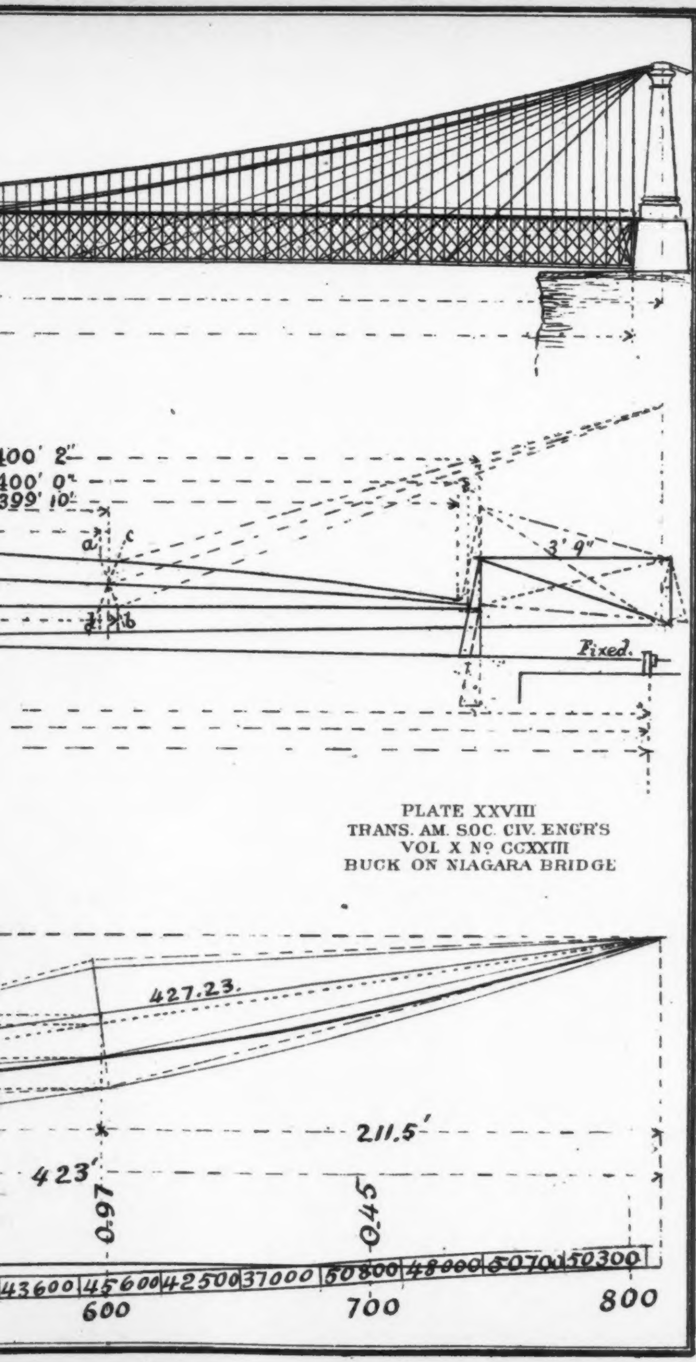


PLATE XXVIII
TRANS. AM. SOC. CIV. ENG'R'S
VOL X No CCXXIII
BUCK ON NIAGARA BRIDGE

There are 628 suspenders to sustain a maximum load of 1 025 tons, or 1.63 tons for each. In no case does the load exceed 2 tons on a suspender. They are of wire rope 4½ inches in circumference, and when new possessed an ultimate strength of 30 tons. Having to shorten some of them, I tested pieces of the wires occasionally by bending them over the corners of the sharp pliers. They bore the test as well as new wire.

The suspenders, as well as all the stays, are attached directly to the iron work of the suspended structure, which insures pemanency of adjustment.

Truss System.

This has been designated to have a factor of safety of 4 for a maximum live load of .8 ton per running foot, and covering a length or 450 feet. The section of each chord is 25 square inches, for a length of 200 feet each side of the middle. The section of the remaining portion, to each end, decreasing as the ordinates of a parabola, in the case of the upper chord, but in that of the lower chord, sufficient section to withstand the thrust of the stays, was continued to the ends. The factor of 4. did not consider the assistance of the stays.

Resistance to Action of Wind.

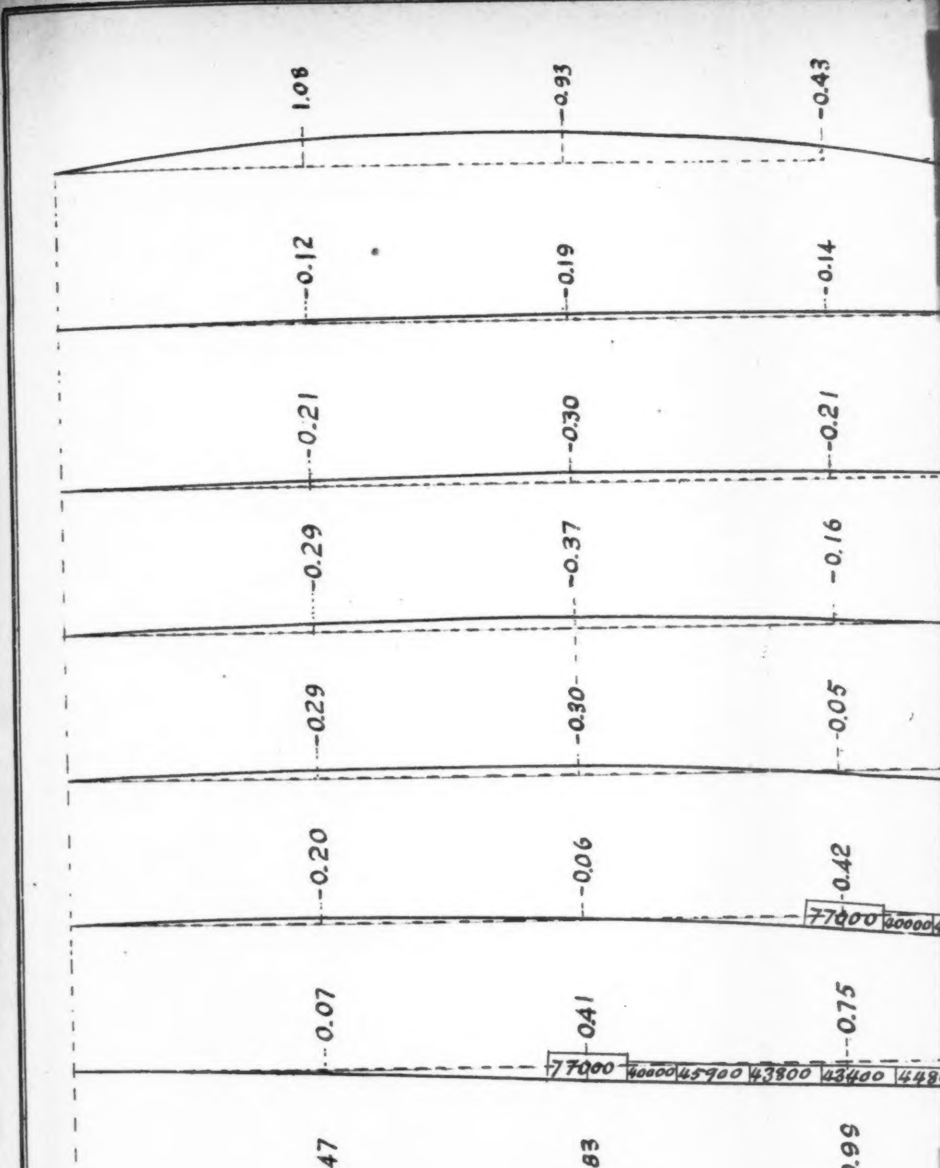
It is not necessary to insert here the calculation for wind pressure, for the reason that the bridge has the same wind stays as before, while the surface exposed is not much more than half what the old structure presented.

The effect of wind upon the bridge is not noticeable to a person standing upon it, for the reason that wind blowing in gusts does not affect it; while a high wind blowing steadily, in a direction transverse to the bridge, merely bends it three or four inches to leeward and holds it there while the wind continues.

In conclusion, I would remark, that in addition to the decrease of weight of suspended superstructure, the effect of live load upon the cables is considerably less than in the case of the old structure, for the following reasons:

1st. The load is distributed over a greater length.

2d. At about each quarter several stays pass vertically downward and are secured to rocks on the banks of the river. The old trusses were not strong enough to resist the bending effect of heavy train loads beginning at one end and extending to the middle of the bridge ; consequently the unloaded quarter would rise sufficiently to cause a heavy tension on the vertical stays of that quarter, which stress must of course be added to the weight of the live load.



1.08
0.93
0.43
0.12
0.19
0.14
0.21
0.30
0.21
0.29
0.37
0.16
0.29
0.30
0.05
0.20
0.06
0.42
77000
80000
0.07
0.41
0.75
77000
40000
45900
43800
43400
0.47
0.83
0.99
77000
40000
45900
43800
43400
44800
43600
45600
42500
0.58
0.94
1.03
77000
40000
45900
43800
43400
44800
43600
45600
42500
37000
50800
48000
0 Feet.
100 Feet
200
300

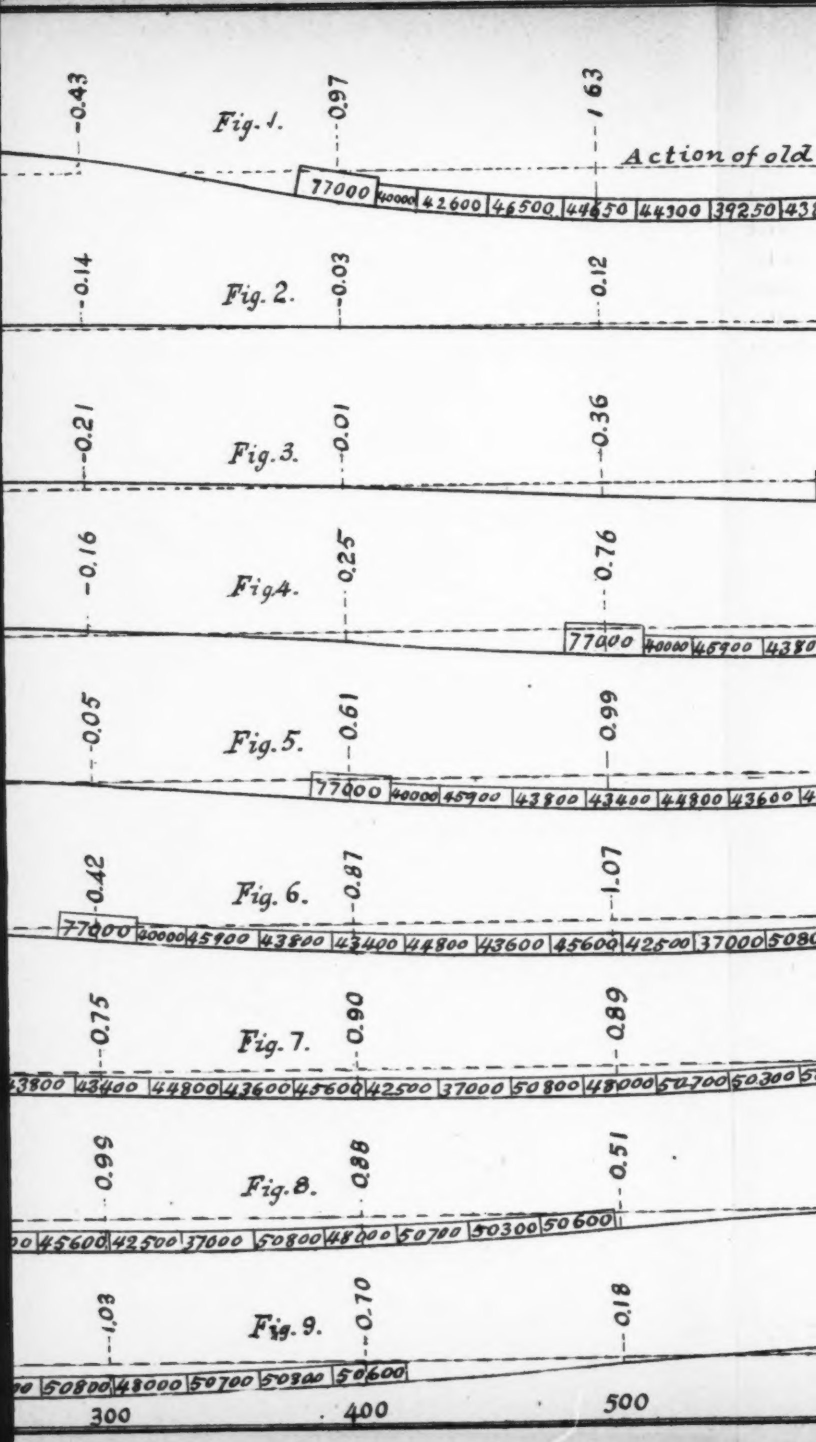
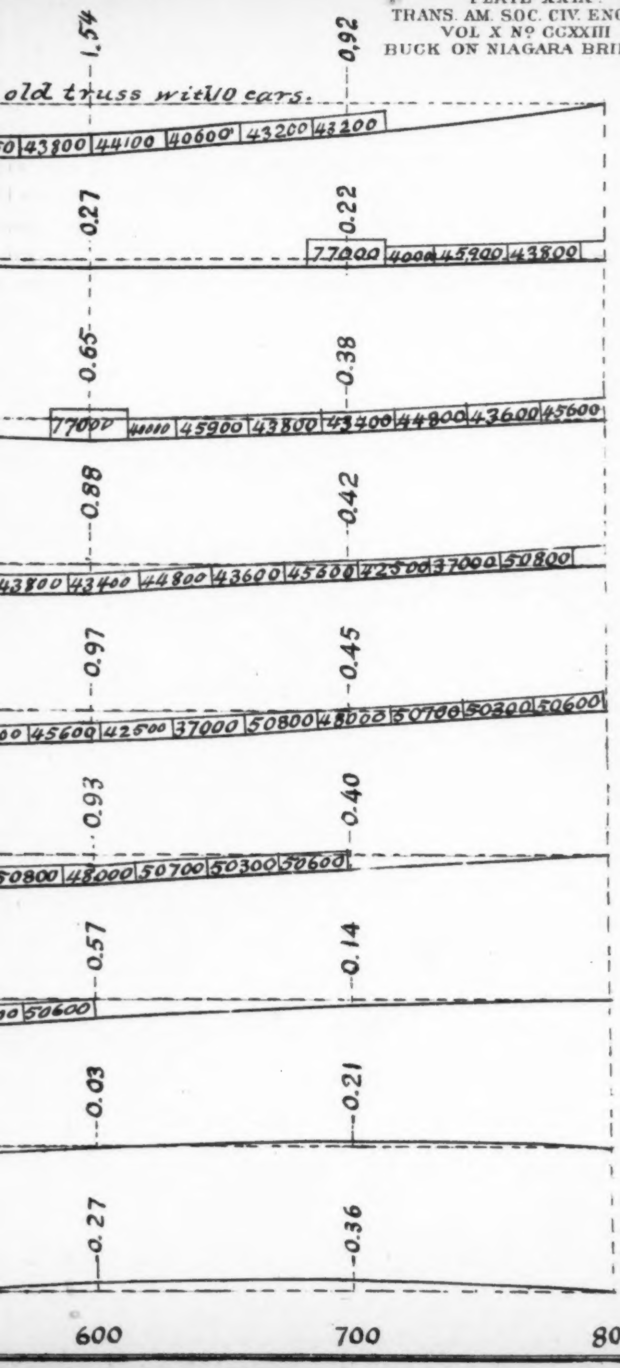


Fig. 1.
-0.43
-0.97
-1.63
Action of old
77000
40000
42600
46500
44650
44300
39250
Fig. 2.
-0.14
-0.03
-0.12
Fig. 3.
-0.21
-0.01
-0.36
Fig. 4.
-0.16
0.25
0.76
77000
40000
45900
Fig. 5.
-0.05
0.61
0.99
77000
40000
45900
43800
43400
44800
43600
Fig. 6.
0.42
0.87
1.07
77000
40000
45900
43800
43400
44800
43600
45600
42500
37000
Fig. 7.
0.75
0.90
0.89
43800
43400
44800
43600
45600
42500
37000
50800
48000
50700
50300
Fig. 8.
0.99
0.88
0.51
45600
42500
37000
50800
48000
50700
50300
50600
Fig. 9.
1.03
-0.70
0.18
50800
48000
50700
50300
50600
300
400
500

PLATE XXIX.
TRANS. AM. SOC. CIV. ENG'R'S
VOL X Nº CCXXIII
BUCK ON NIAGARA BRIDGE



AMERICAN SOCIETY OF CIVIL ENGINEERS.

INSTITUTED 1852.

TRANSACTIONS.

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CCXXIV.

(Vol. X.—July, 1881.)

THE FLOW OF THE SUDBURY RIVER, MASSACHUSETTS, FOR THE YEARS 1875 TO 1879.

By ALPHONSE FTELEY, Member of the Society.

PRESENTED AT THE ANNUAL MEETING, NOVEMBER 3D, 1879.

DISCUSSION

On Rainfall and the Flow of Streams, by J. JAMES R. CROES, ASHBEL WELCH, JOSEPH P. DAVIS, FRANCIS COLLINGWOOD, CLEMENS HERSCHEL, GEORGE W. DRESSER, SAMUEL L. SMEDLEY, JULIUS E. HILGARD, THOMAS C. CLARKE, ALFRED G. COMPTON, OCTAVE CHANUTE, MARSHALL M. TIDD, WILLIAM R. HUTTON, CHARLES E. EMERY.

PAPER BY A. FTELEY.

The accompanying tables and diagrams, marked Plates XXX, XXXI, XXXII and XXXIII, are the results of daily gaugings made on Sudbury River for several years, in connection with the new works erected by the City of Boston for an additional supply of water.

The river, above the point where its waters are diverted, is formed by two principal affluents; the larger, draining about two-thirds of the gathering grounds, rises in a hilly district and flows afterwards through an open valley with extensive swampy areas; the other affluent flows

through a hilly district and, although draining a territory only one-half as extensive, it has sometimes, after heavy rains, a volume as great as the larger stream.

The whole water-shed controlled by the works covers seventy-eight square miles; a portion of it (from one-sixth to one-eighth) is covered with woods, the balance, with the exception of areas occupied by several villages, has a general agricultural character.

There being along the streams some small mill-ponds which are irregularly filled and emptied during the dry season, the daily flow at such times, below these ponds, does not represent fairly the yield of the water-shed; for this reason, the minimum flow has been shown in the tables for no less than one week.

The diagrams show the daily flow of the river for the years 1875 to 1878, inclusive, before the storage reservoirs were finished. In 1879 these basins, situated above the point where the water is diverted and measured, were filled for the first time, and the daily flow of the river, especially during the dry period, could not be ascertained with the same accuracy as it depended largely on the measurement of the level of water surfaces six hundred acres in area; it is for this reason that the diagram for 1879, Plate XXXIV, shows only the monthly averages of flow.

In 1874, before Sudbury River had been decided upon as a source of water supply, some observations were taken twice a week to form an idea of the flow; although the measurements were not made then by accurate methods, the results are sufficiently approximate to give an estimate of the volume flowing at the time of each observation. There were about ten observations taken every month, and the flow varied between the following limits, viz.:

In February,	from	109	to	480	million	gallons	per 24 hours.
" March	"	100	"	384	"	"	"
" April	"	95	"	256	"	"	"
" May	"	96	"	414	"	"	"
" June	"	32	"	380	"	"	"
" July	"	10	"	62	"	"	"
" August	"	8.7	"	82	"	"	"
" September	"	8	"	22	"	"	"
" October	"	8.1	"	25	"	"	"
" November	"	8.3	"	64	"	"	"
" December	"	24	"	62	"	"	"

An analysis of the data furnished will show the extent of water-shed, and the storage capacity which can be relied upon for furnishing a given daily supply of water, uniformly throughout the year, for a similar period and for a stream of similar description ; but longer and more severe droughts must be expected.

The water shed controlled by the Sudbury River works is equal to seventy-eight square miles ; it has been calculated that with a complete system of storage reservoirs—eight in number—the supply would be equal to forty million gallons per day throughout the year. For the present, three storage reservoirs only, draining the same water shed, have been constructed; their joint capacity is equal to two thousand million gallons, and it was expected that the supply would be equal to twenty million gallons per day throughout the year, this computation, according to the best practice, was made on a liberal basis, but the experience of this season has shown that ample allowances must be made for extreme dry years.

The diagrams and tables explain themselves, but a brief description of the methods used for the gauging may be found sufficiently interesting to be mentioned. Plate XXXV shows the relative positions of the various points where the observations are taken.

The flow of the river is checked by a low timber dam *A*, built temporarily to direct the water into Farm Pond. From Farm Pond the water was originally taken from the city supply through a temporary channel *C*, of rectangular form made of sheet piling, and presenting a regular smooth surface. Since 1878, the water for the city supply has been taken through the new conduit *D*.

The level of Farm Pond is consequently under control, but its natural water shed, about one square mile, is included in the gathering grounds.

From the above it is seen that, in order to compute with accuracy the total yield of the river and of Farm Pond it is necessary to measure, first : The flow of water for the supply of the city through the channels *C* or *D*. Second : The storage in Farm Pond. Third : The flow of the river water wasted at the dam *A*.

The amount of water diverted for the city supply through the temporary channel *C* was computed from tables established by careful experiments made with floating tubes, and indicating the flow corre-

sponding to various heights of water in the channel, and to various inclinations of the water surface.

From year to year, or oftener, when found necessary, new experiments were made, and corrections rendered necessary by the slight changes in the shape of the bottom and sides of the channel, were entered in the tables.

The daily computations of volume were frequently checked by the readings of a current meter.

Since the abandonment of the temporary channel in 1878 the water used for the city supply has been measured in the conduit *D*, by the usual methods modified by local observations.

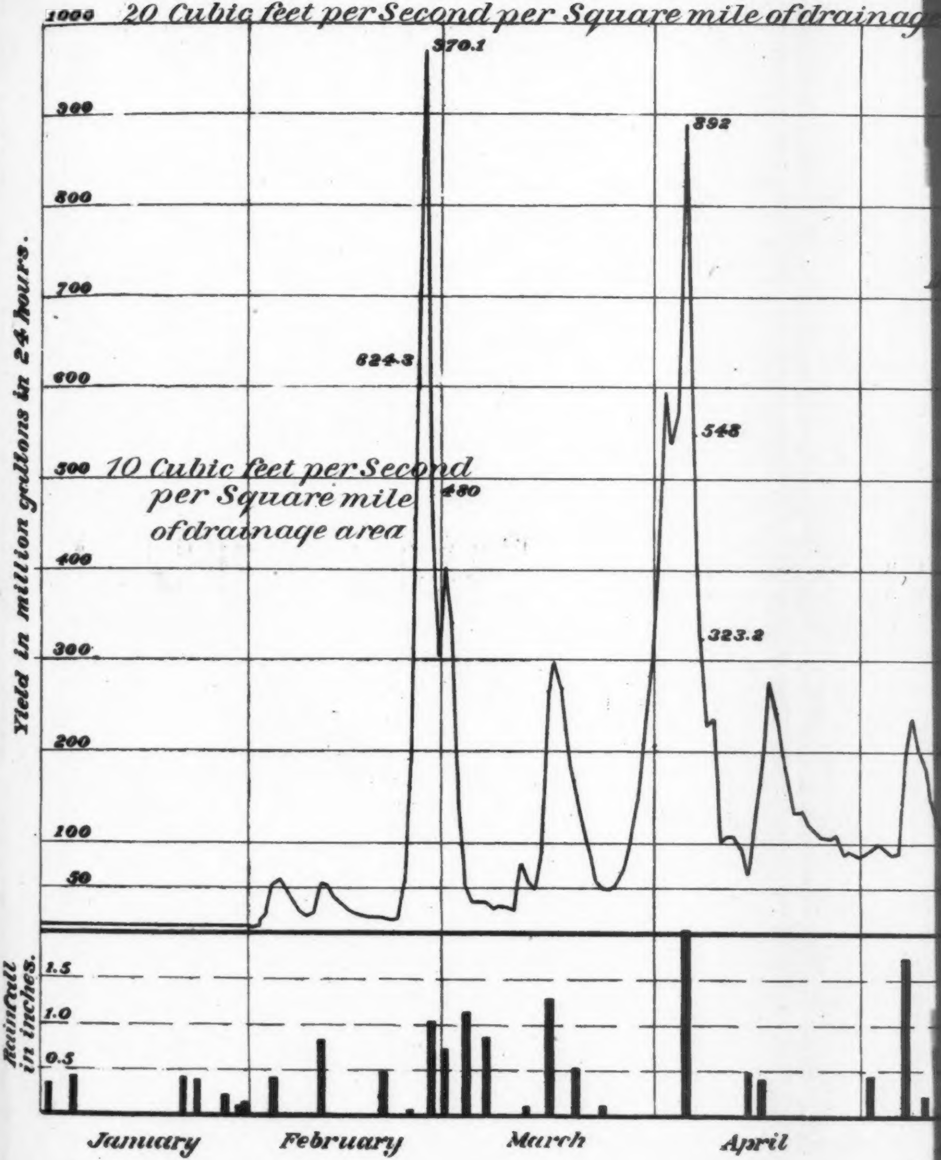
The storage of Farm Pond is computed daily by observations of its level, the water area, two hundred acres in extent, having been previously ascertained by actual survey.

The portion of the river flow which does not take place through Farm Pond is generally measured at the dam *A*.

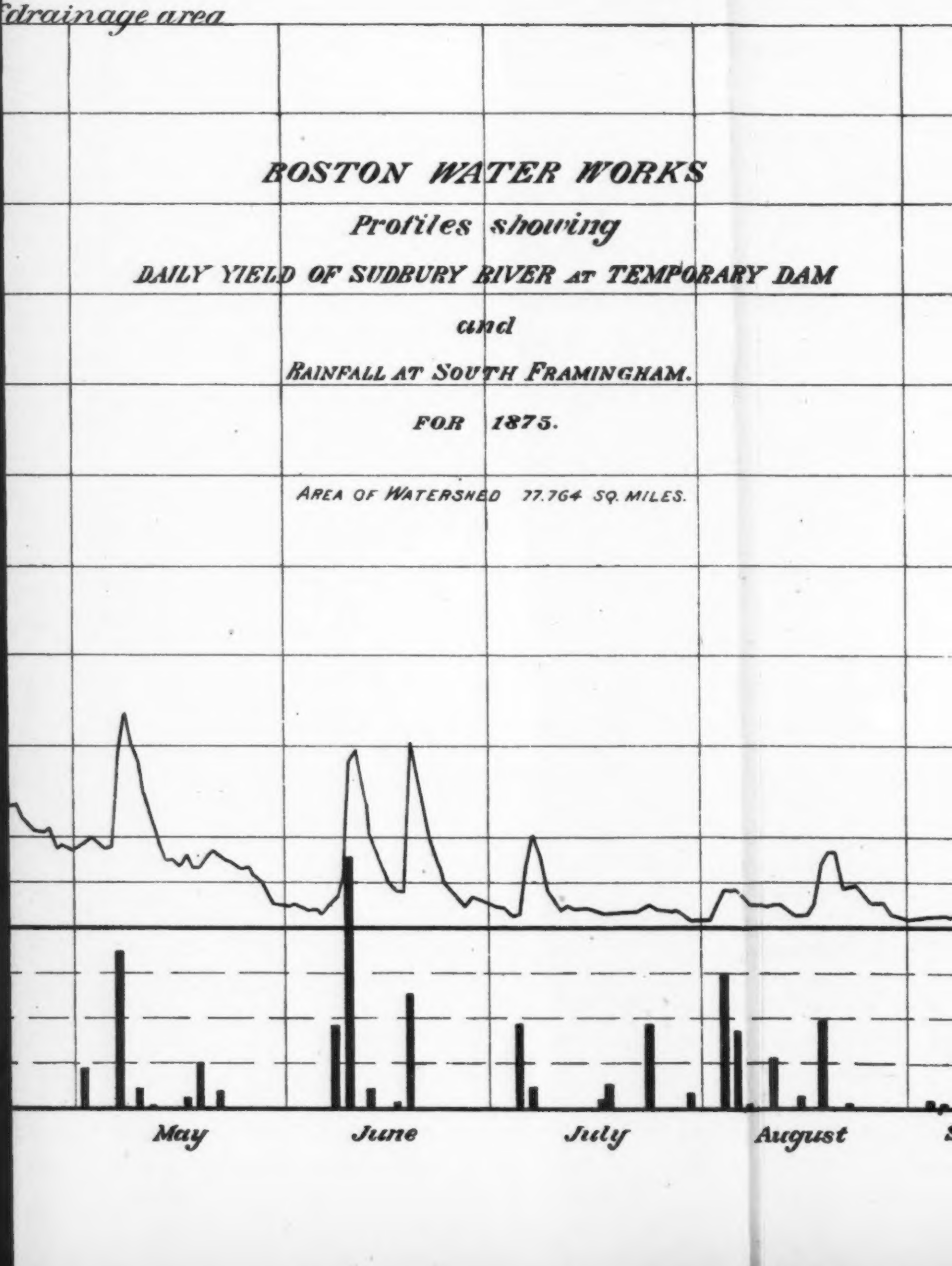
The upper part of the dam, one hundred and twenty feet long, is made of movable flash-boards forming a well defined, level crest four inches in thickness; when the dam is not in use, the river flows through a large flume, twenty feet wide, placed on one side of the dam with its bottom on the river bed. This flume is controlled by movable stop-planks.

With the exception of the periods when the river is swollen by freshets, when the gaugings are made elsewhere, the flow is measured either over the dam or through the side flume.

When the flow takes place over the dam it is computed by means of tables deduced from measurements made previously over a crest of similar construction. When the flow takes place through the flume it is measured in two ways; if it does not exceed eighty million gallons per day, it is measured over three weirs placed across the flume in the stop-plank grooves; if it exceeds that quantity, the volume is deduced, by observation of the depth of water in the flume, from tables established by numerous measurements made with a reliable current meter for all stages of the water; the daily computations are frequently checked by use of the meter, and when slight discrepancies are observed between its readings and the tables, owing to small changes in the condition of the channel below the dam, corrections are made accordingly. From what precedes it may be seen that all the observations necessary for the

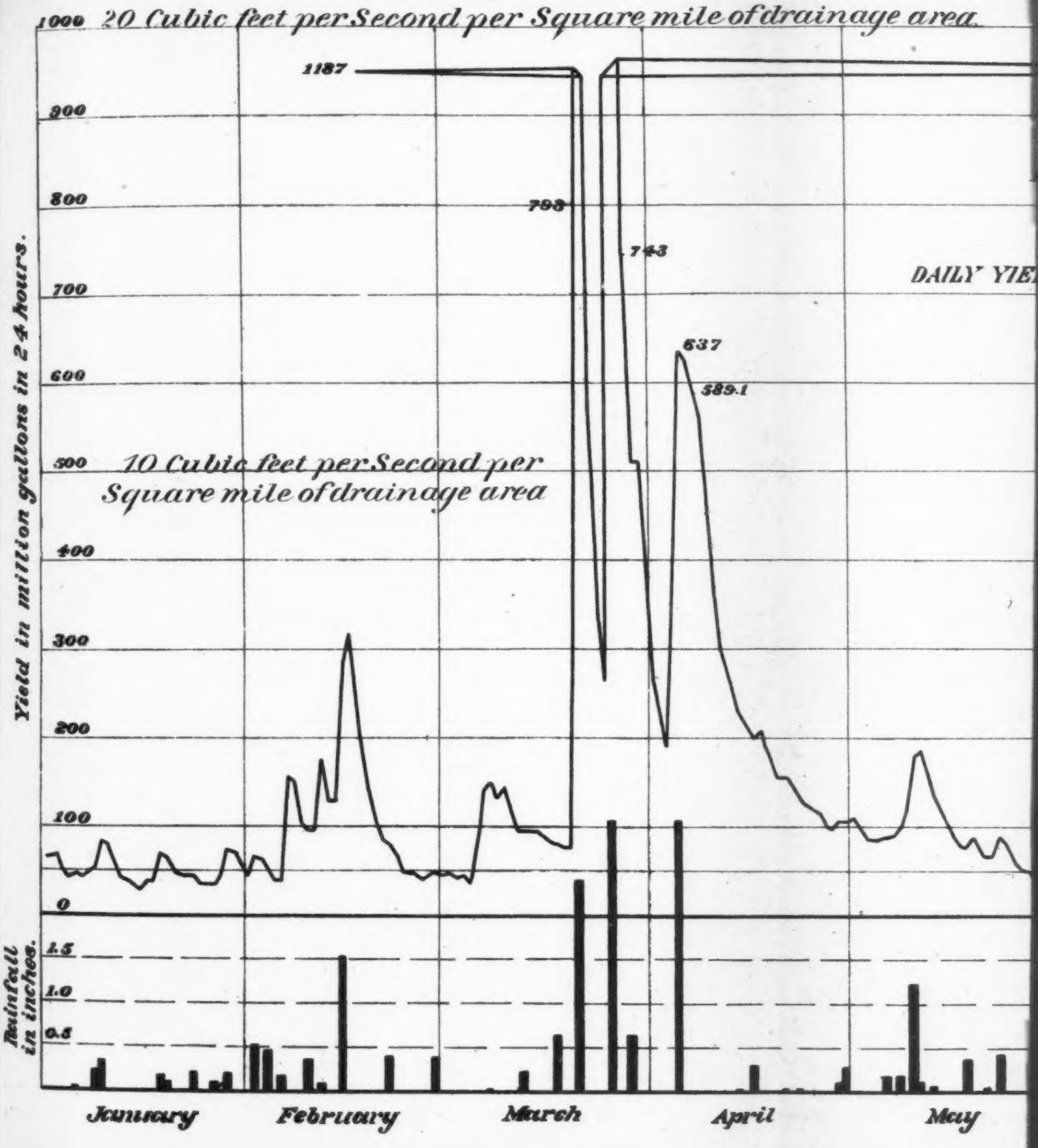


20 Cubic feet per Second per Square mile of drainage
10 Cubic feet per Second per Square mile of drainage area
Yield in million gallons in 24 hours.
1000
900
800
700
600
500
400
300
200
100
50
970.1
892
624.3
548
480
323.2
Rainfall in inches.
1.5
1.0
0.5
January
February
March
April

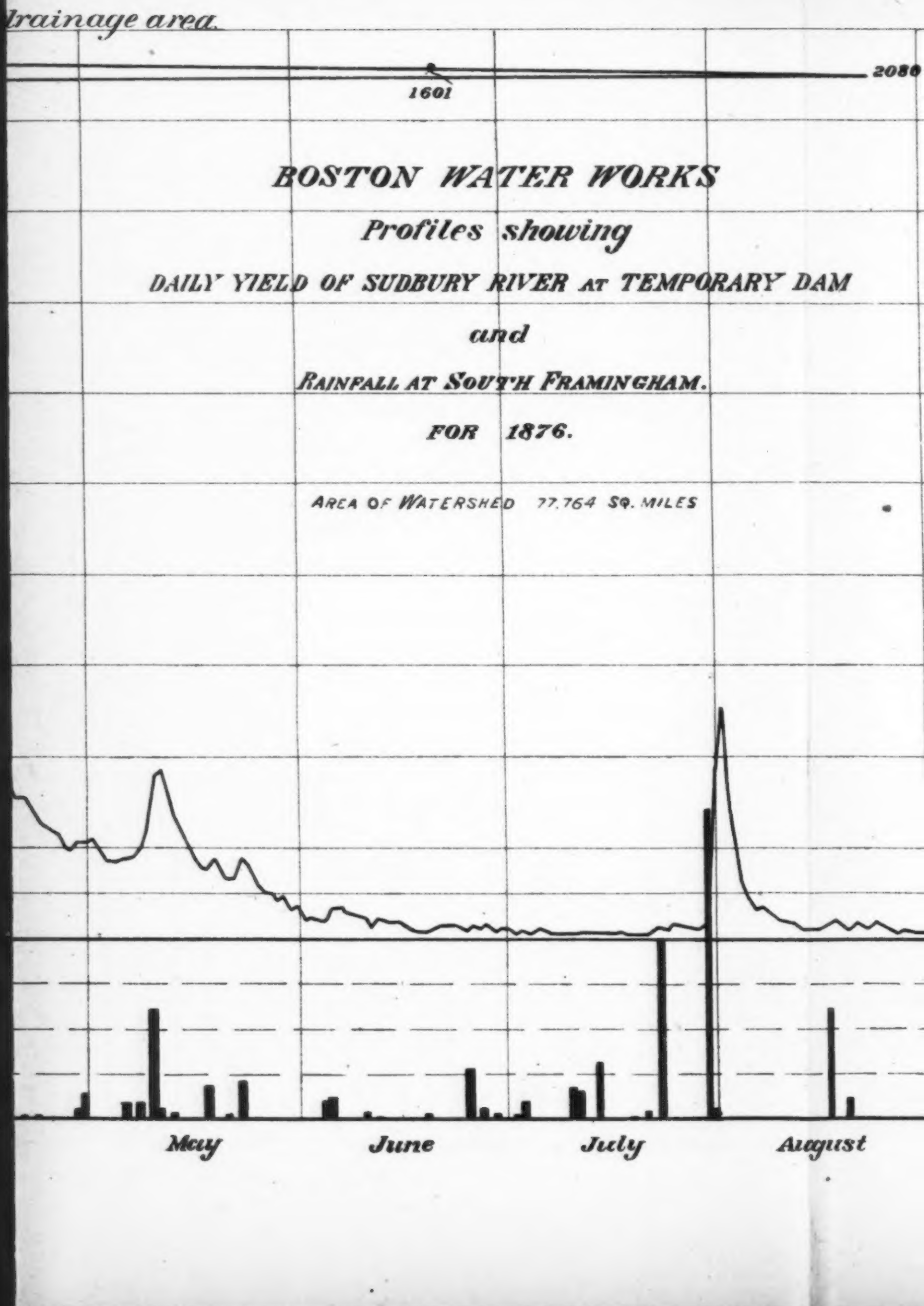


drainage area
BOSTON WATER WORKS
Profiles showing
DAILY YIELD OF SUDBURY RIVER AT TEMPORARY DAM
and
RAINFALL AT SOUTH FRAMINGHAM.
FOR 1875.
AREA OF WATERSHED 77.764 SQ. MILES.
May
June
July
August

PLATE XXX.
TRANS. AM. SOC. CIV. ENGR'S
VOL X Nº CCXXIV
FTELEY ON FLOW OF
SUDBURY RIVER
1000
900
800
700
600
500
400
300
200
100
0
Yield in million gallons in 24 hours.
1.5
1.0
0.5
Rainfall in inches.
September
October
November
December



20 Cubic feet per Second per Square mile of drainage area.
10 Cubic feet per Second per Square mile of drainage area
DAILY YIE
Yield in million gallons in 24 hours.
Rainfall in inches.
1000
900
800
700
600
500
400
300
200
100
0
1.5
1.0
0.5
1187
798
743
637
589.1
January
February
March
April
May



drainage area.
1601
2080
BOSTON WATER WORKS
Profiles showing
DAILY YIELD OF SUDBURY RIVER AT TEMPORARY DAM
and
RAINFALL AT SOUTH FRAMINGHAM.
FOR 1876.
AREA OF WATERSHED 77.764 SQ. MILES
May
June
July
August

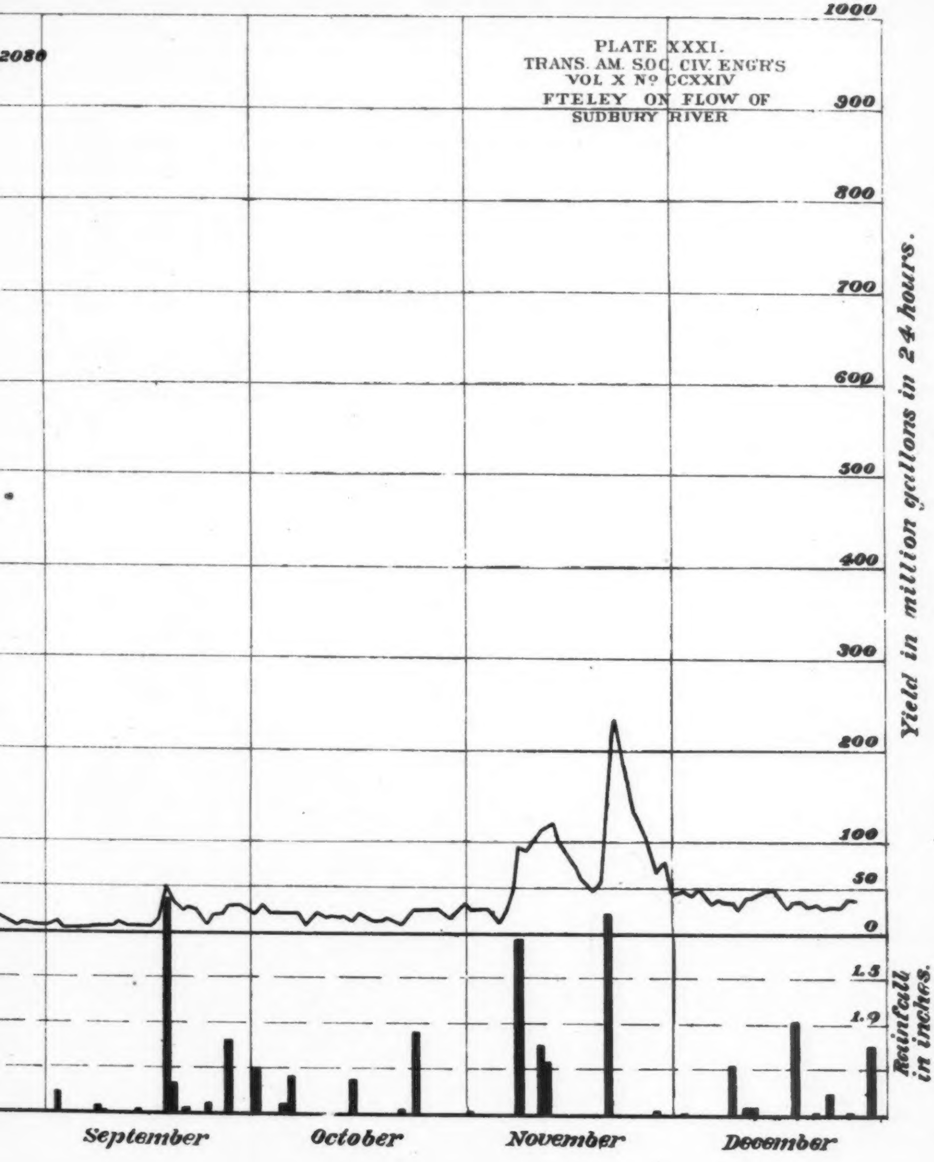
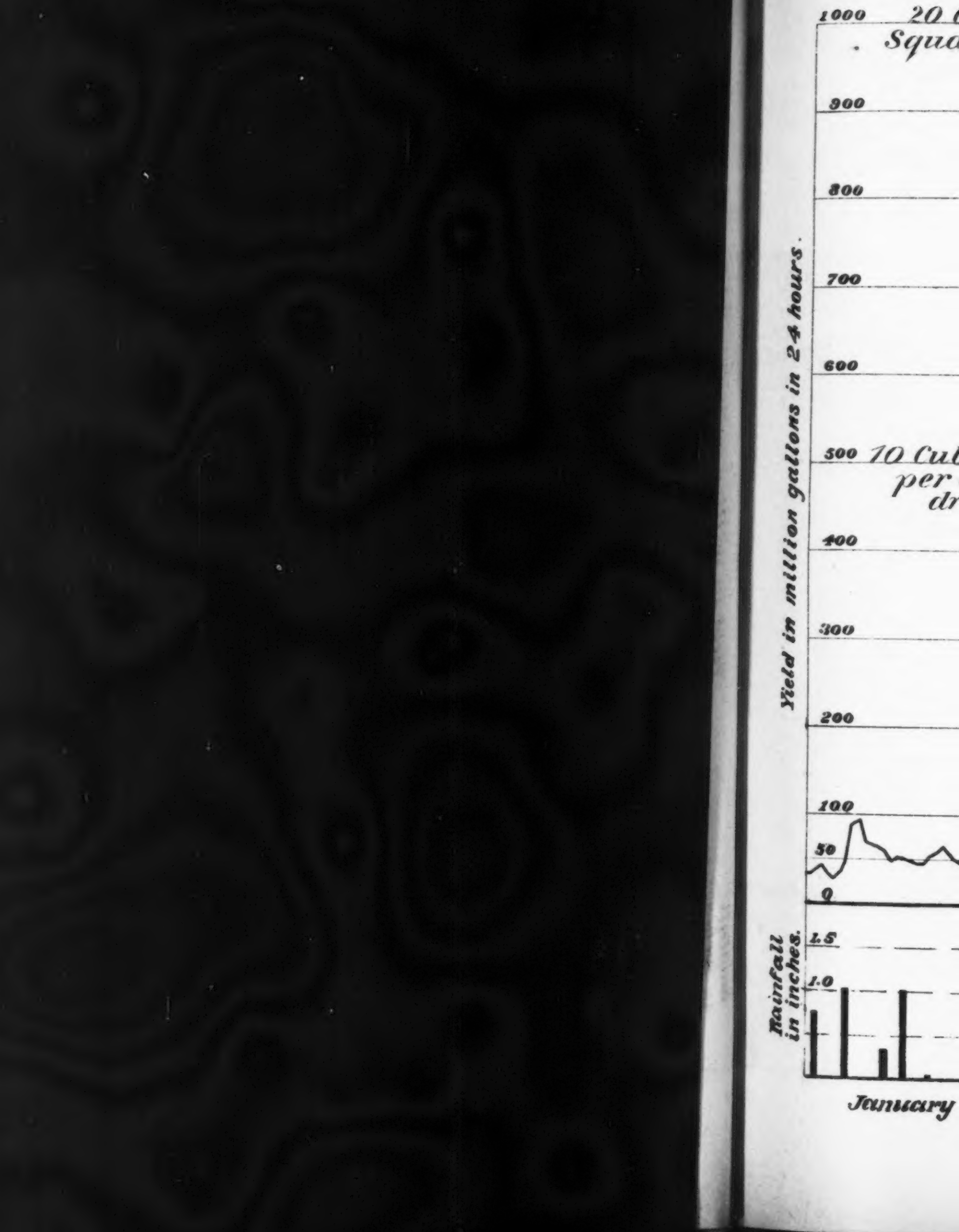
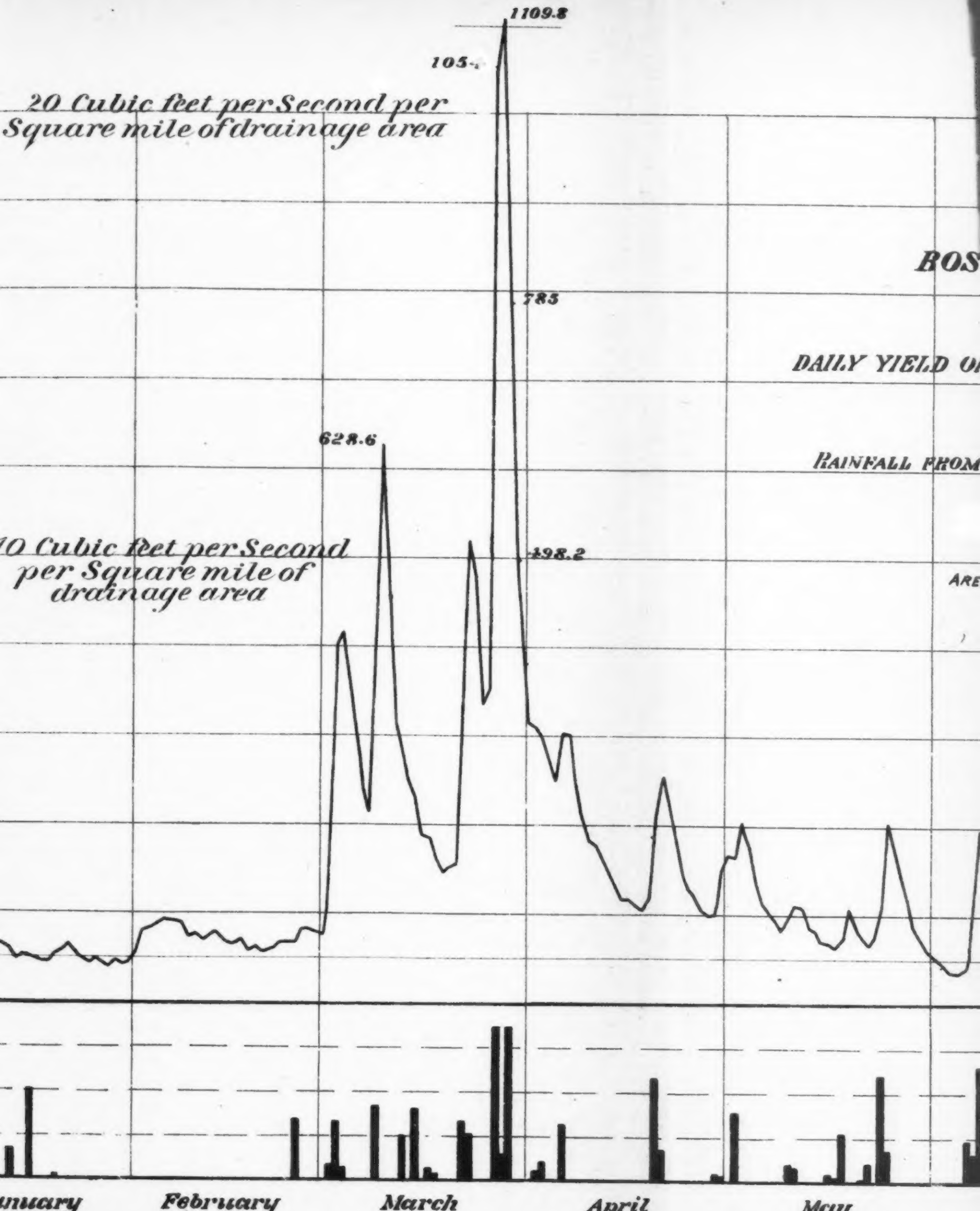
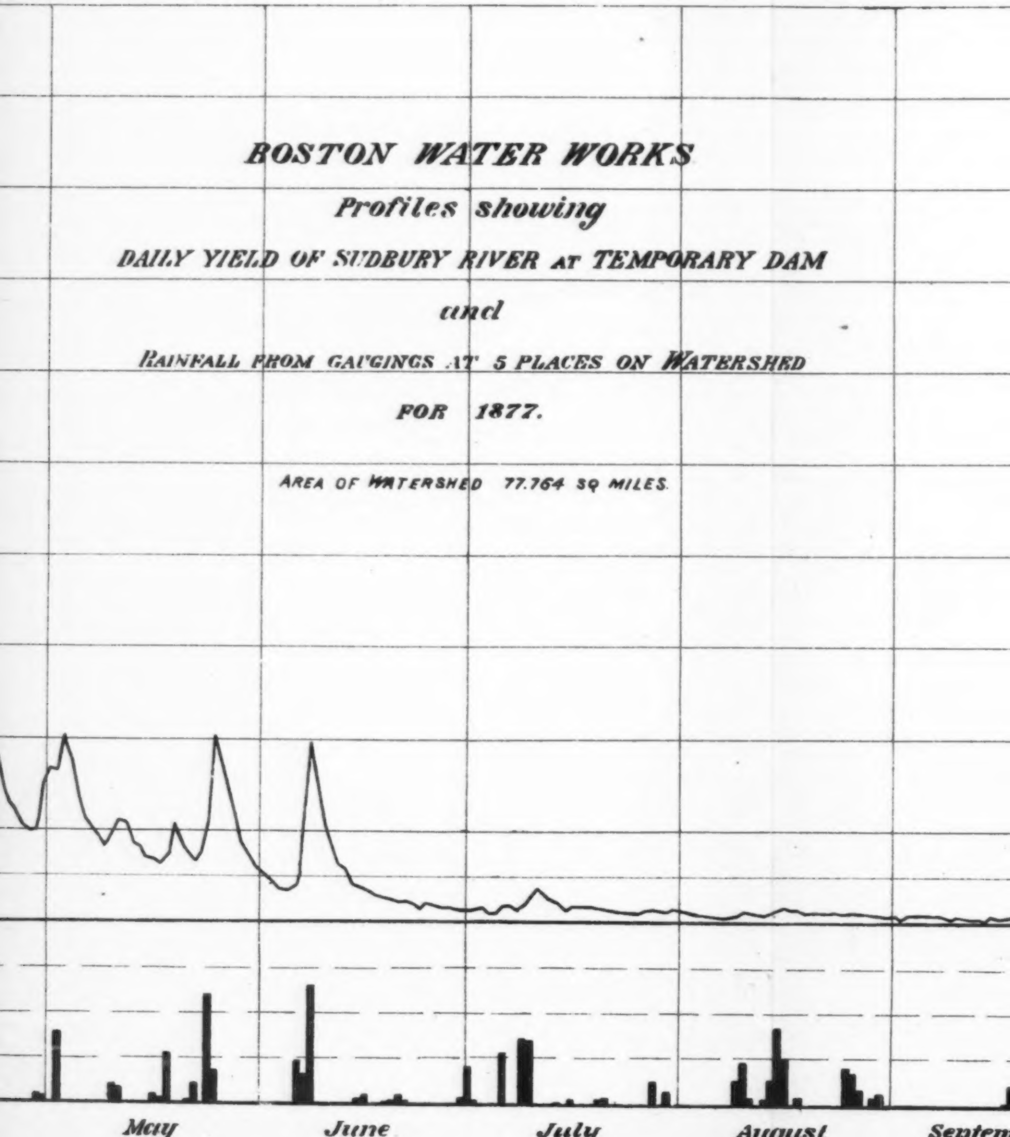


PLATE XXXI.
TRANS. AM. SOC. CIV. ENG'R'S
VOL X Nº CCXXIV
FTELEY ON FLOW OF
SUDBURY RIVER
2080
1000
900
800
700
600
500
400
300
200
100
50
0
1.5
1.0
Yield in million gallons in 24 hours.
Rainfall in inches.
September
October
November
December



Yield in million gallons in 24 hours.
1000
900
800
700
600
500
400
300
200
100
50
0
Rainfall in inches.
1.5
1.0
January


1109.8
105.
20 Cubic feet per Second per Square mile of drainage area
785
628.6
198.2
10 Cubic feet per Second per Square mile of drainage area
BOS
DAILY YIELD O
RAINFALL FROM
ARE
nuary
February
March
April
May



BOSTON WATER WORKS
Profiles showing
DAILY YIELD OF SUDBURY RIVER AT TEMPORARY DAM
and
RAINFALL FROM GAUGINGS AT 5 PLACES ON WATERSHED
FOR 1877.
AREA OF WATERSHED 77.764 SQ MILES.
May
June
July
August
Septem

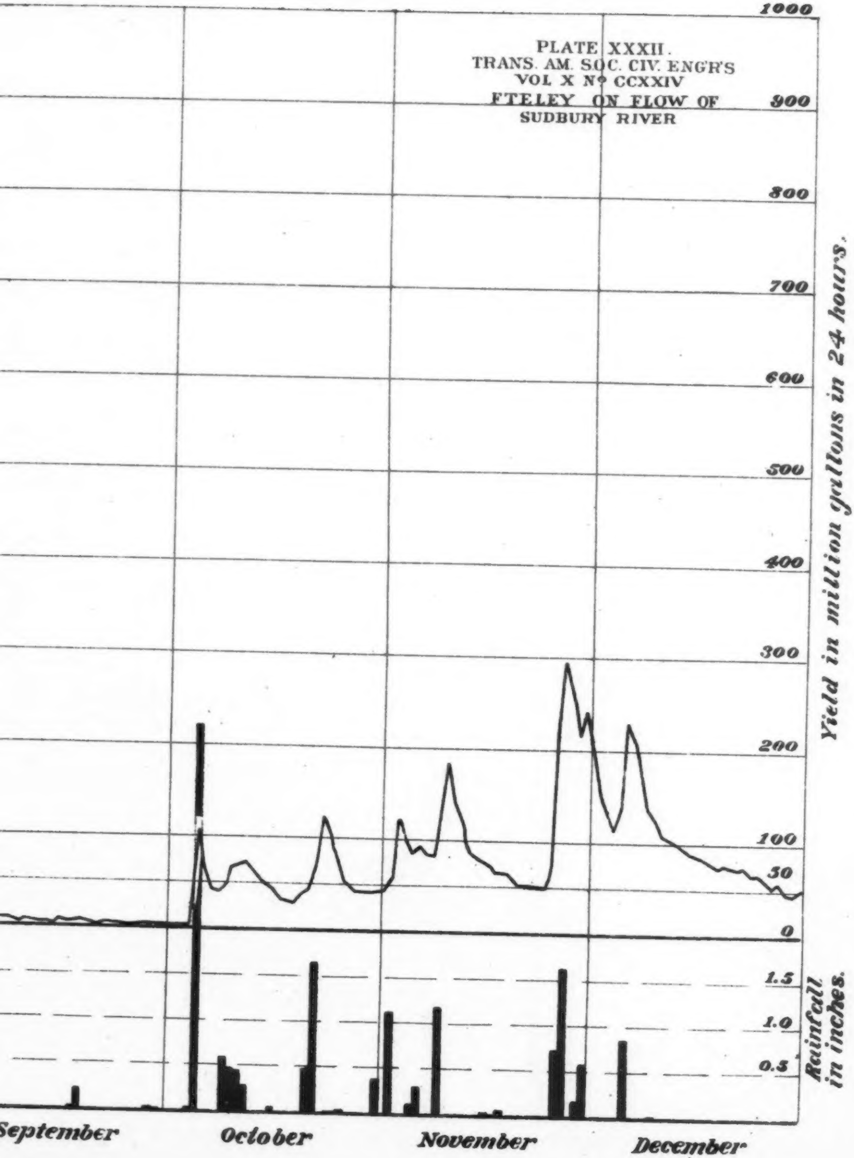
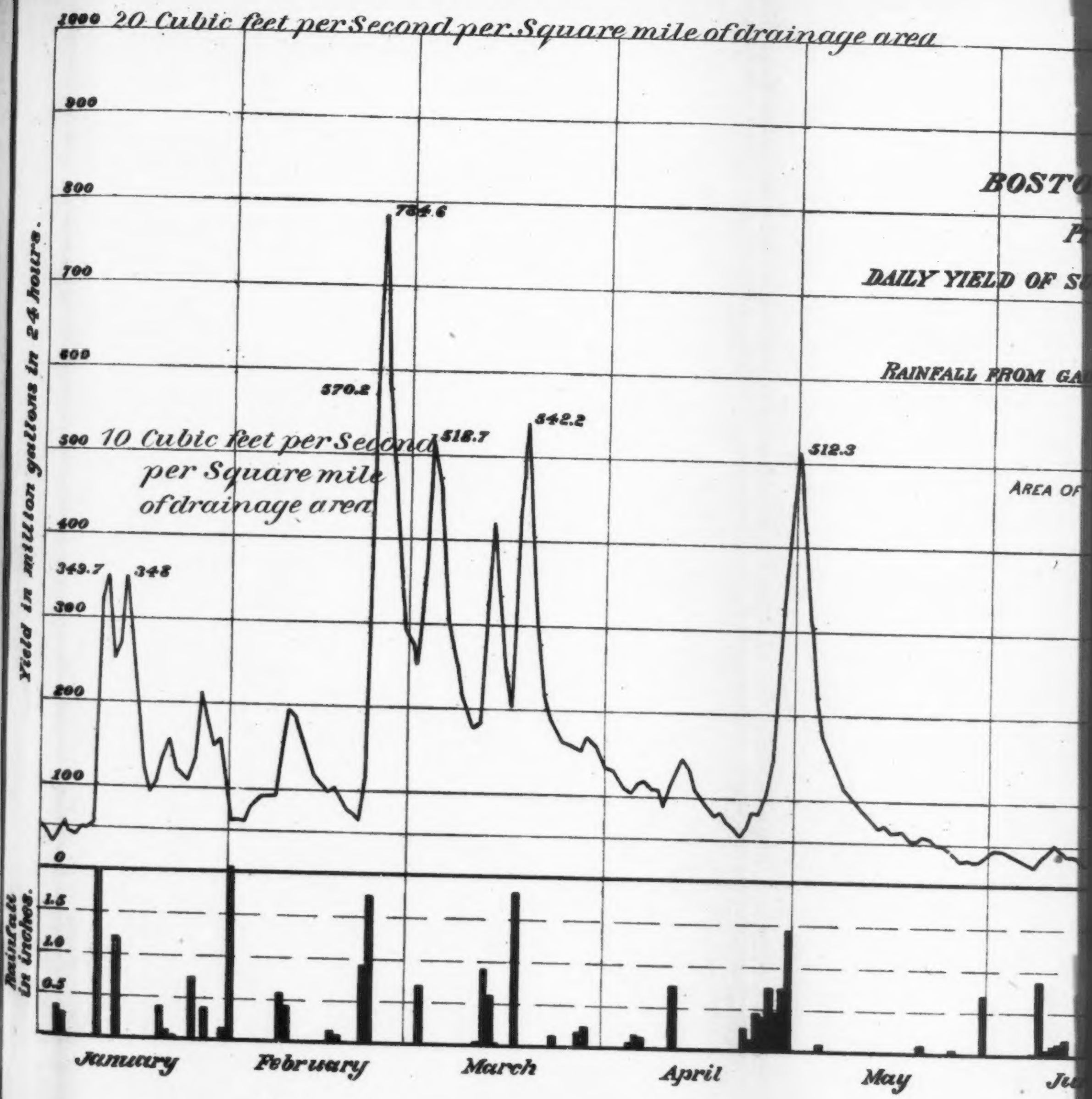


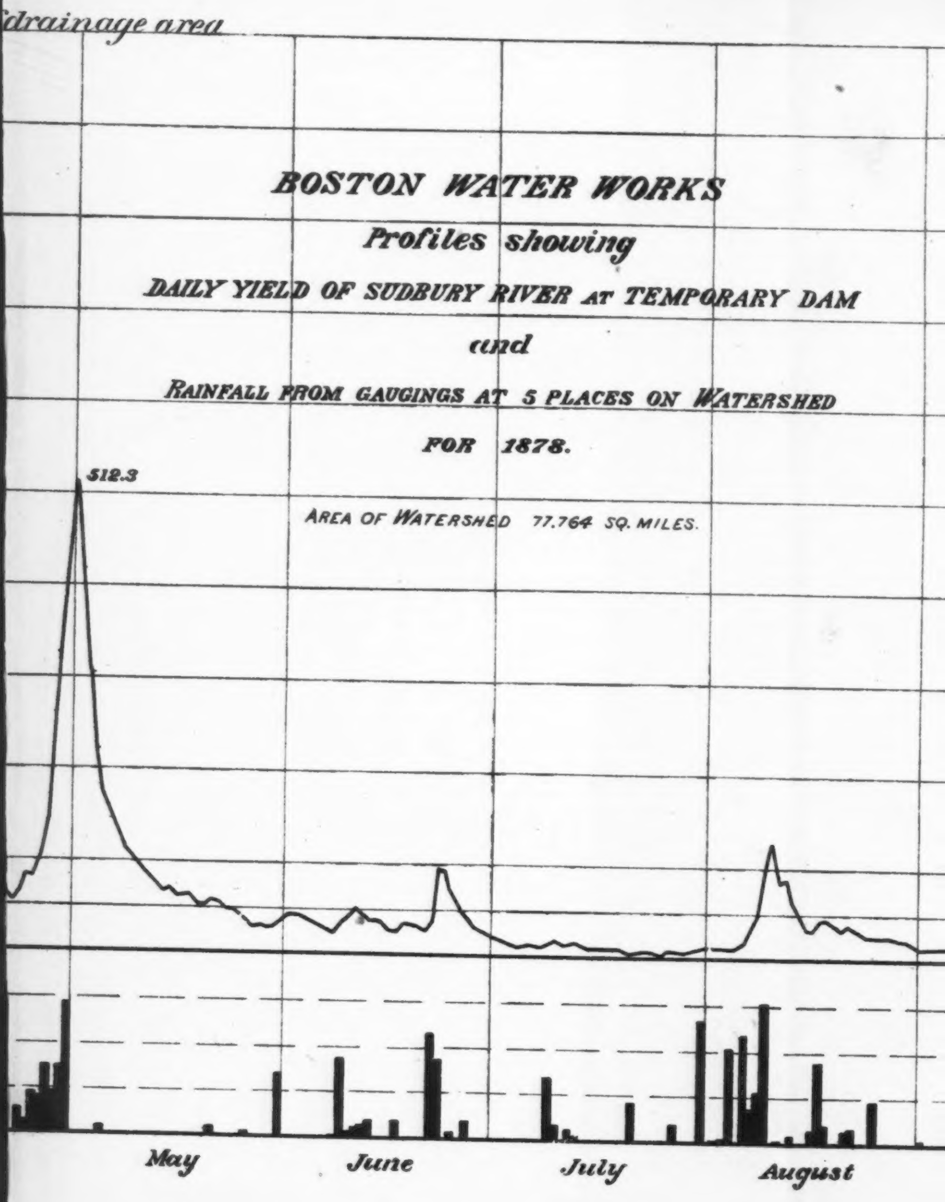
PLATE XXXII.
TRANS. AM. SOC. CIV. ENG'R'S
VOL X Nº CCXXIV
FTELEY ON FLOW OF
SUDBURY RIVER
1000
900
800
700
600
500
400
300
200
100
50
0
Yield in million gallons in 24 hours.
1.5
1.0
0.5
Rainfall in inches.
September
October
November
December

Rainfall in inches.

Yield in million gallons in 24 hours



1000
20 Cubic feet per Second per Square mile of drainage area
900
800
700
600
500
400
300
200
100
0
Yield in million gallons in 24 hours.
784.6
570.2
518.7
542.2
512.3
349.7
348
10 Cubic feet per Second per Square mile of drainage area
BOSTO
DAILY YIELD OF S
RAINFALL FROM GA
AREA OF
Rainfall in inches.
1.5
1.0
0.5
January
February
March
April
May



drainage area
BOSTON WATER WORKS
Profiles showing
DAILY YIELD OF SUDBURY RIVER AT TEMPORARY DAM
and
RAINFALL FROM GAUGINGS AT 5 PLACES ON WATERSHED
FOR 1878.
512.3
AREA OF WATERSHED 77.764 SQ. MILES.
May
June
July
August

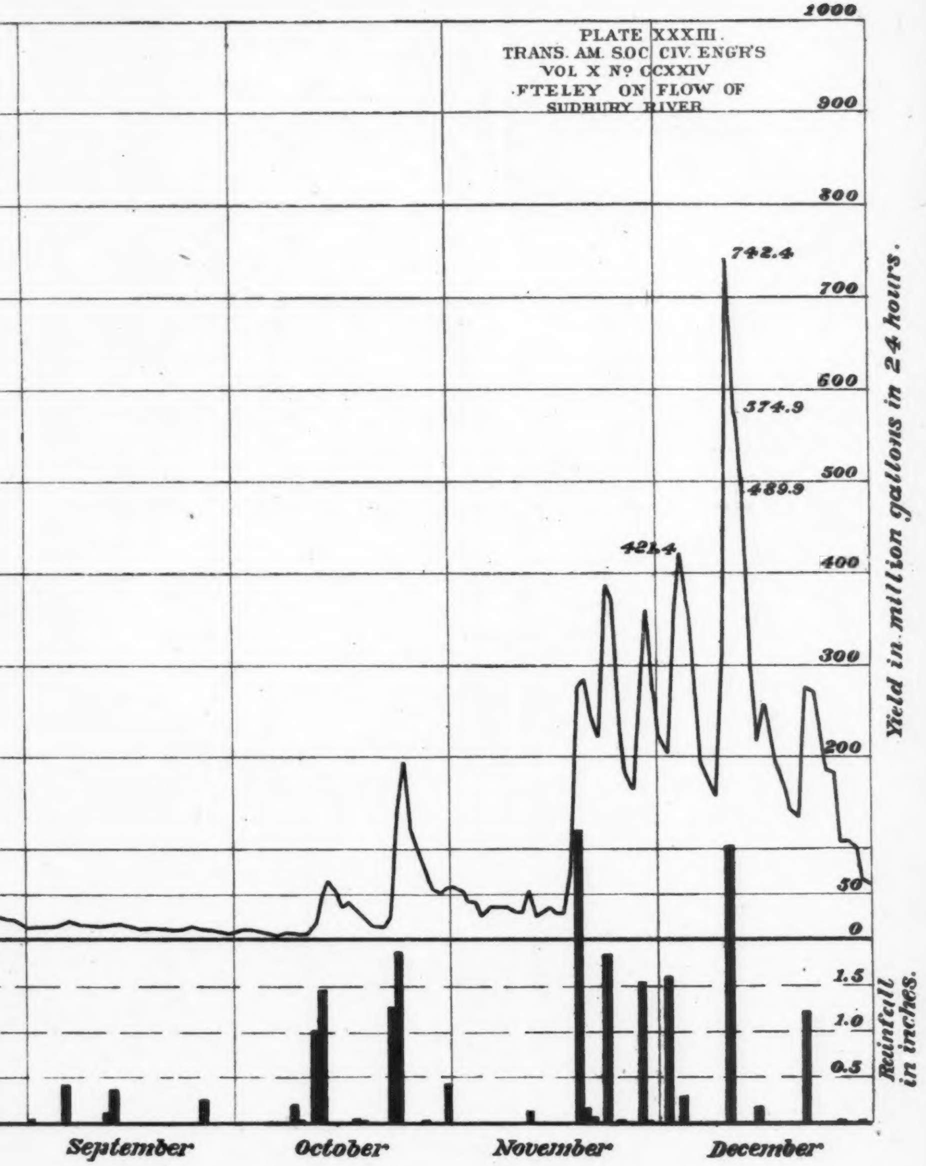
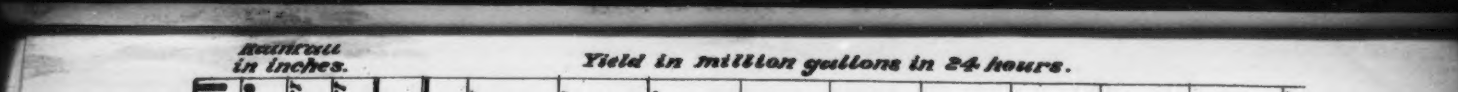
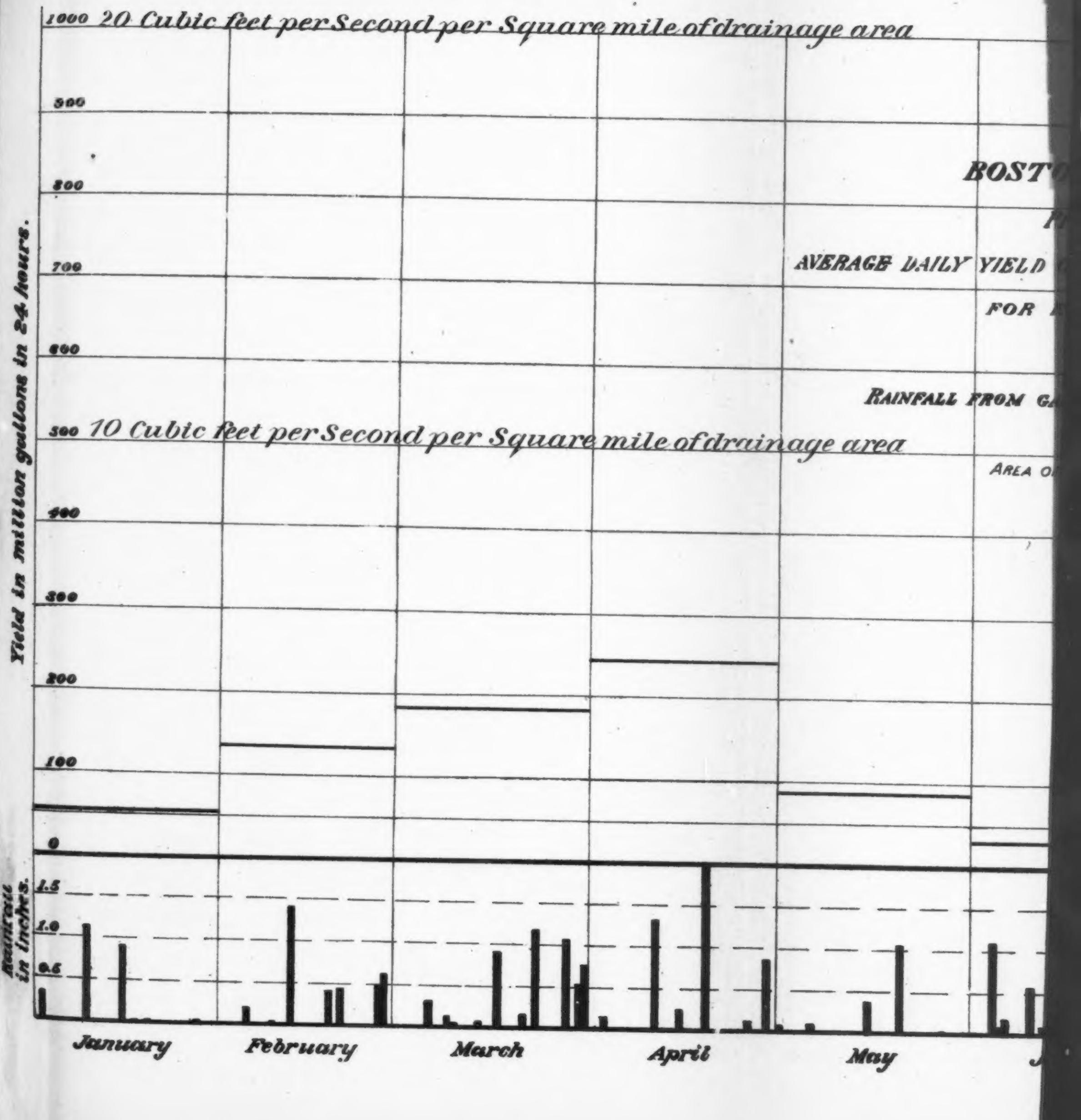
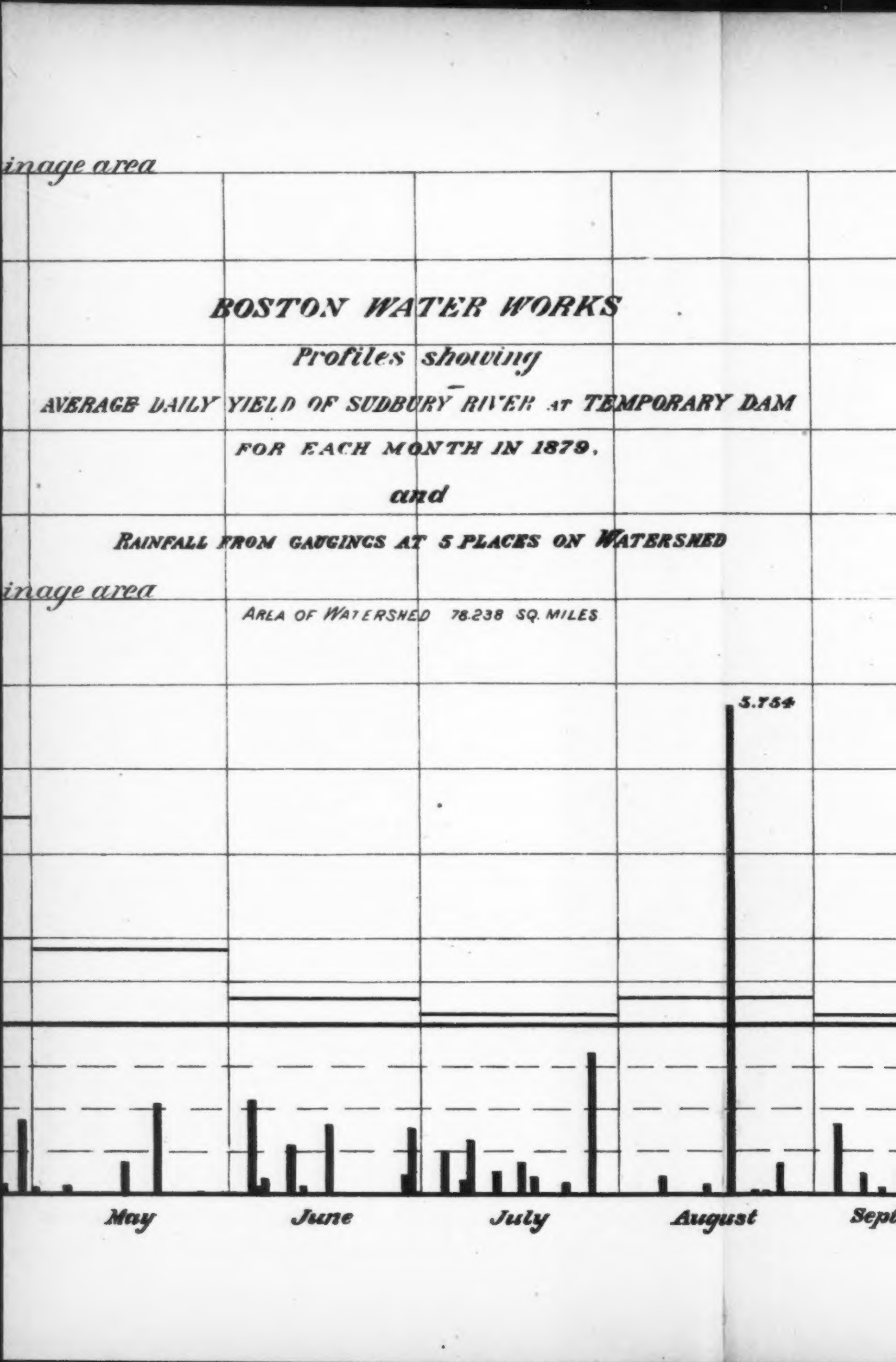


PLATE XXXIII.
TRANS. AM. SOC. CIV. ENG'R'S
VOL X Nº CCXXIV
FTELEY ON FLOW OF
SUDBURY RIVER
1000
900
800
742.4
700
600
574.9
500
489.9
421.4
400
300
200
50
0
1.5
1.0
0.5
Yield in million gallons in 24 hours.
Rainfall in inches.
September
October
November
December


Rainfall in inches.
Yield in million gallons in 24 hours.



1000 20 Cubic feet per Second per Square mile of drainage area
900
800
700
600
500 10 Cubic feet per Second per Square mile of drainage area
400
300
200
100
0
Yield in million gallons in 24 hours.
Rainfall in inches.
1.5
1.0
0.5
January
February
March
April
May
BOSTO
AVERAGE DAILY YIELD
FOR
RAINFALL FROM GA
AREA O


inage area
BOSTON WATER WORKS
Profiles showing
AVERAGE DAILY YIELD OF SUDBURY RIVER AT TEMPORARY DAM
FOR EACH MONTH IN 1879.
and
RAINFALL FROM GAUGINGS AT 5 PLACES ON WATERSHED
inage area
AREA OF WATERSHED 78.238 SQ. MILES
5.754
May
June
July
August
Sept

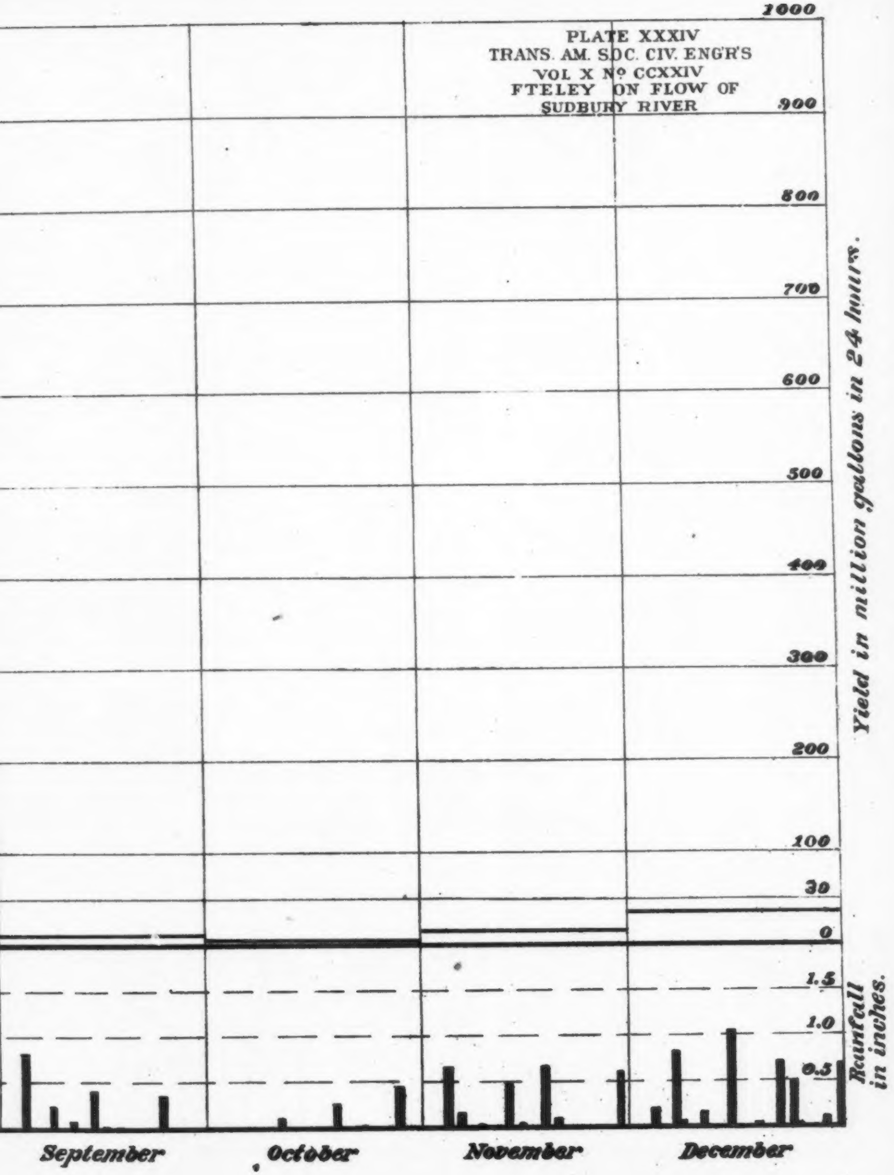


PLATE XXXIV
TRANS. AM. SOC. CIV. ENGR'S
VOL X Nº CCXXIV
FTELEY ON FLOW OF
SUDBURY RIVER
1000
900
800
700
600
500
400
300
200
100
30
0
1.5
1.0
0.5
Yield in million gallons in 24 hours.
Rainfall in inches.
September
October
November
December

measurement of the water at the dam, whether it is allowed to flow over it or through the side flume, are reduced to the registering of the water level.

The levels, which in 1875 were taken three times a day, were afterwards ascertained by continuous diagrams recorded by a self-registering float. The float is contained in a box which can be connected, according to the way the water is made to flow, either with the still water above the dam or with the flume at its side. Plate XXXVI.

An endless sheet of paper, moving between guides on a horizontal table, advances at the rate of one foot in twenty-four hours under the action of the brass roll *A*, which is moved by clock work.

The float *O*, is suspended by a slender metallic thread from the pulley *C*; the slack of the thread is taken by the weight *D*. The motion of the pulley, when acted upon by the float, is transmitted by the wheels *E F* to the horizontal bar *G*, which carries the pencil *H*, and moves on two small rolls. The range of the variations of level at the dam being about eight feet, it is often necessary, in order to remain within the limits of the paper, to reduce considerably the motion of the pencil; it is for this reason that the main pulley *C* has four grooves of different diameters. When the largest diameter is used, the motion of the pencil is one-eighth of that of the float; when the smallest is used, the pencil moves as the float; the largest has been used almost exclusively. The difference of temperature has no perceptible effect on the length of the wire, and the loss of motion in the transmission of the movements of the float does not cause any appreciable error. In the winter a kerosene lamp suspended in the float-box and a small kerosene stove kept burning in the room containing the apparatus, are sufficient to prevent freezing.

In order to render the diagram independent from the side motion of the endless paper, a stationary pencil *K* records a line which represents constantly a given height of the float ascertained by actual measurement of the level of the water, and the variations of level indicated by the diagram are measured by the distances between the two pencil lines.

The diagrams, when taken from the apparatus, are divided by vertical lines into sections, for each of which the average ordinate is established by planimeter measurement. These sections vary in length according to the frequency and magnitude of the changes in the water level, being made very short when the irregularities are frequent and large, or extending the whole length of a day or more if the level

remains nearly constant. The error due to this method of computing the average ordinates is small when the sections into which the the diagrams are divided are judiciously determined.

When the variations of the flow are large, or when the flow is to be turned to or from Farm Pond, some considerable time is needed to place or remove the flash boards on the stop-plank; but the recording apparatus requires very little attention.

The office work necessary for computing the flow is also inconsiderable at ordinary times.

The accompanying Plate XXXVII, showing the level of the water for two days, has been prepared at a scale of one-fifth of the working diagrams for the purpose of illustrating the work of the apparatus. It represents within a small compass a considerable range of variations.

As the water at the dam stands at very different levels, according to its mode of flowing, the line traced by the movable pencil as it rises or falls does not give, at first sight, any correct idea of the increase or decrease of the flow. It indicates simply the height at which the water stands and the depth of water (whether over the crest of the weirs or in the flume) from which the volume is computed.

The line *O O*, traced by the stationary pencil, represents on the diagram elevation 146 above base, and is approximately straight, the side motion of the endless paper being small.

At the beginning of the diagram, on February 12th, the flow of the river is supposed small (3 700 000 gallons in twenty-four hours), and it passes over one weir occupying one-third of the width of the flume. At 6 P. M., there being an indication of an increase of flow, owing to a rise in the temperature, the three weirs are put in, occupying the whole width of the flume, and the level falls. The flow continues to increase, and at 2 P. M. on the 13th, after a rain, it is found necessary to remove all obstacles in the flume; as a consequence, the diagram shows a sudden fall of the water surface; the volume of the river keeps on increasing, but commences to fall towards the end of the day.

All this time the water has been wasted, but at 12 M. of the 15th it becomes necessary to turn the water into Farm Pond. The stop-planks are put in the flume, and for one hour the water rises behind the dam. Then it overflows, and from that time to the 21st the flow takes place over the crest of the dam.

PLATE XXXV
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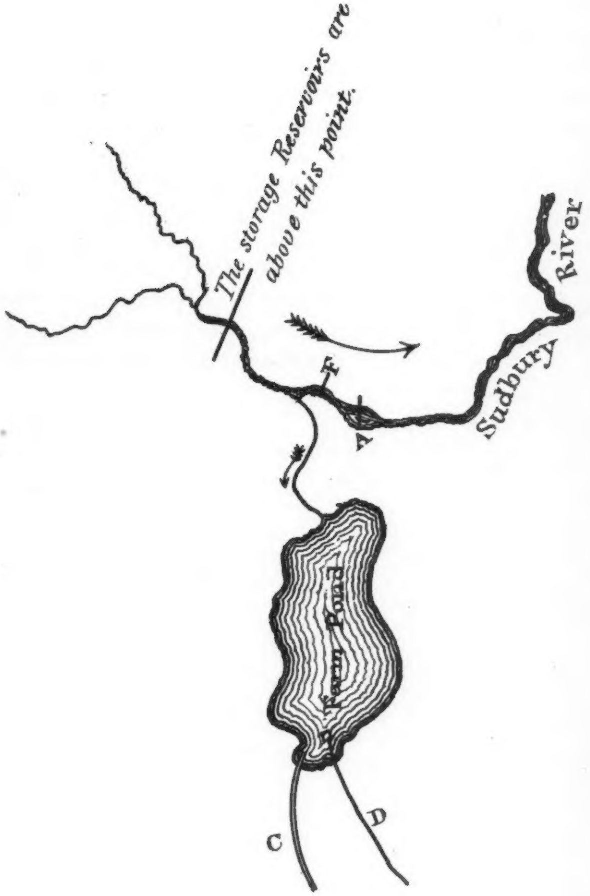
FTELEY ON FLOW OF
SUDBURY RIVER



The ordinates in the diagram indicate the sections into which it is divided to compute the flow.

When the volume of the river is so large that the flash-boards of the dam have to be removed to avoid damage from flowage, the flow cannot be gauged with accuracy by the same methods, and the volume is then measured from time to time with a current meter at a point *F* (Plate XXXV) of the stream where it is enclosed at the sides by smooth vertical walls, and where the bottom is formed by a plank floor securely fastened to the bed of the stream. A foot bridge thrown across the river at that point enables the observer to take the measurements with ease.

The flow of the river has been measured several times simultaneously at the dam by the methods previously described, and at the foot bridge by current meter, and the results have always been found to agree closely.

At the end of March, 1876, the flow was unusually large, and none of the gauging apparatus could be used, the results recorded for that time were calculated from several observations taken a little higher up on the river at mill dams and road bridges.

YIELD OF SUDBURY RIVER.

Table showing Yield, Rainfall, and the Proportion of the Rainfall Represented by the Yield.

Month.	1875.				
	Total Yield of Sudbury River. Gallons.	Average Daily Yield. Gallons.	Rainfall. Inches.	Amount of Rainfall represented by flow in River.	
				Inches.	Percentage of total Rainfall.
January	248 000 000	8 000 000	2.42	0.184	7.60%
February	3 257 800 000	116 350 000	3.15	2.411	76.54 "
March	3 867 200 000	124 748 400	3.74	2.862	76.52 "
April	7 113 200 000	237 106 700	3.23	5.263	162.94 "
May	2 863 100 000	92 358 100	3.56	2.119	59.52 "
June	2 029 100 000	67 636 700	6.24	1.501	24.05 "
July	774 700 000	24 990 300	3.57	0.573	16.05 "
August	954 000 000	30 774 200	5.53	0.706	12.77 "
September	483 800 000	16 126 700	3.43	0.358	10.44 "
October	1 557 500 000	50 241 900	4.85	1.152	23.75 "
November	3 038 000 000	101 266 700	4.83	2.248	46.54 "
December	1 407 300 000	45 396 800	0.94	1.041	110.74 "
	27 593 700 000	75 599 200	45.49	20.418	44.88 "

Month.	1876.				
	Total Yield of Sudbury River. Gallons.	Average Daily Yield. Gallons.	Rainfall. Inches.	Amount of Rainfall represented by flow in River.	
				Inches.	Percentage of total Rainfall.
January	1 550 300 000	50 009 700	1.83	1.147	62.68%
February	3 084 500 000	106 362 100	4.21	2.282	54.20 "
March	10 691 100 000	344 874 200	7.43	7.911	106.47 "
April	7 680 400 000	256 013 300	4.197	5.683	135.41 "
May	2 744 000 000	88 516 100	2.763	2.031	73.51 "
June	517 500 000	17 250 000	2.040	0.383	18.77 "
July	441 100 000	14 229 000	9.134	0.326	3.57 "
August	976 900 000	31 512 900	1.720	0.723	42.03 "
September	430 200 000	14 340 000	4.614	0.318	6.89 "
October	563 000 000	18 161 300	2.241	0.417	18.61 "
November	2 537 800 000	84 593 300	5.764	1.878	32.58 "
December	1 093 100 000	35 261 300	3.620	0.809	22.35 "
	32 309 900 000	88 278 400	49.563	23.908	48.24 "

PLATE XXXVI
TRANS. AM. SOC. CIV. ENG'R'S
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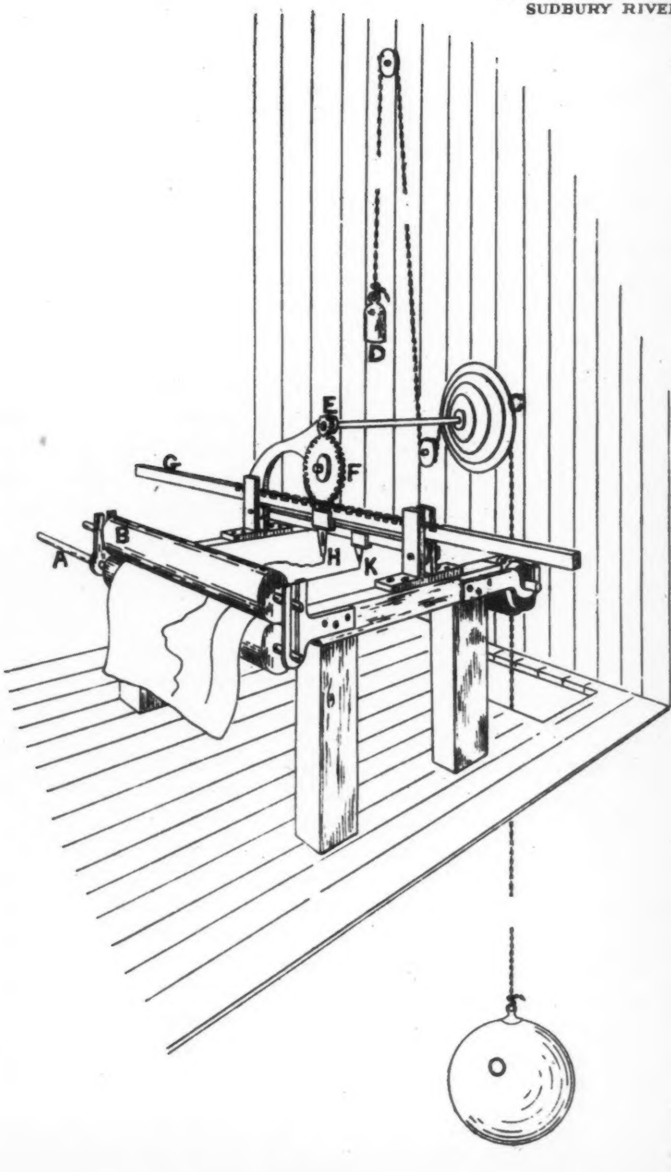
FTELEY ON FLOW OF
SUDBURY RIVER



YIELD OF SUDBURY RIVER.

Table showing Yield, Rainfall, and the Proportion of the Rainfall Represented by the Yield.

Month.	1877.				
	Total Yield of Sudbury River. Gallons.	Average Daily Yield. Gallons.	Rainfall. Inches.	Amount of Rainfall represented by flow in River.	
				Inches.	Percentage of total Rainfall.
January	1 586 900 000	51 190 300	3.216	1.174	36.50%
February	2 066 900 000	73 817 900	0.739	1.529	206.90 "
March	11 604 100 000	374 325 800	8.357	8.586	102.74 "
April	5 584 100 000	186 136 700	3.435	4.132	120.29 "
May	3 354 200 000	108 200 000	3.702	2.482	67.04 "
June	1 393 000 000	46 433 300	2.425	1.031	42.52 "
July	486 060 000	15 679 400	2.951	0.360	12.20 "
August	291 890 000	9 415 800	3.682	0.216	5.87 "
September	139 006 000	4 633 300	0.323	0.103	31.89 "
October	1 522 400 000	49 109 700	8.515	1.127	13.24 "
November	3 307 300 000	110 243 300	5.803	2.447	42.17 "
December	3 108 900 000	100 287 100	0.870	2.300	264.37 "
	34 444 750 000	94 369 200	44.018	25.487	57.90 "

Month.	1878.				
	Total Yield of Sudbury River. Gallons.	Average Daily Yield. Gallons.	Rainfall. Inches.	Amount of Rainfall represented by flow in River.	
				Inches.	Percentage of total Rainfall.
January	4 362 100 000	140 712 900	5.632	3.228	57.32%
February	5 367 900 000	191 710 700	5.973	3.972	66.50 "
March	8 454 400 000	272 722 600	4.689	6.256	133.42 "
April	3 793 200 000	126 440 000	5.790	2.807	48.48 "
May	3 361 600 000	108 438 700	0.956	2.487	260.15 "
June	1 179 800 000	39 326 700	3.884	0.873	22.48 "
July	309 500 000	9 983 900	2.971	0.229	7.71 "
August	1 146 300 000	36 997 400	6.937	0.848	12.22 "
September	375 100 000	12 503 300	1.291	0.277	21.46 "
October	1 244 300 000	40 138 700	6.417	0.921	14.35 "
November	3 949 000 000	131 633 300	7.024	2.922	41.60 "
December	7 658 800 000	247 058 100	6.367	5.667	89.01 "
	41 202 000 000	112 882 200	57.931	30.487	52.63 "

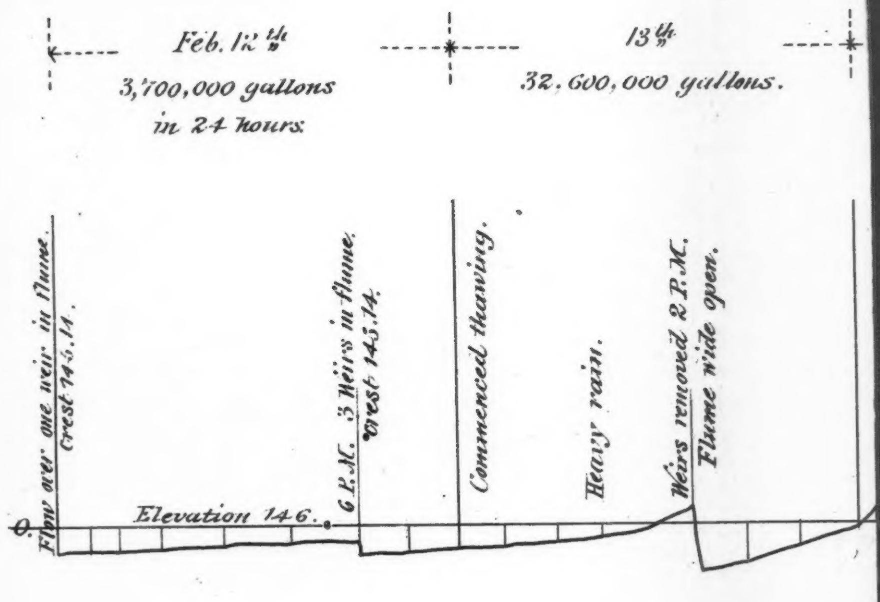
YIELD OF SUDBURY RIVER.

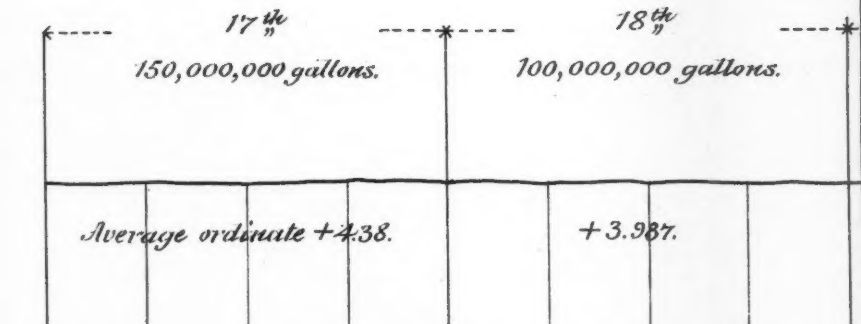
TABLE SHOWING YIELD, RAINFALL, AND THE PROPORTION OF THE RAINFALL REPRESENTED BY THE YIELD.

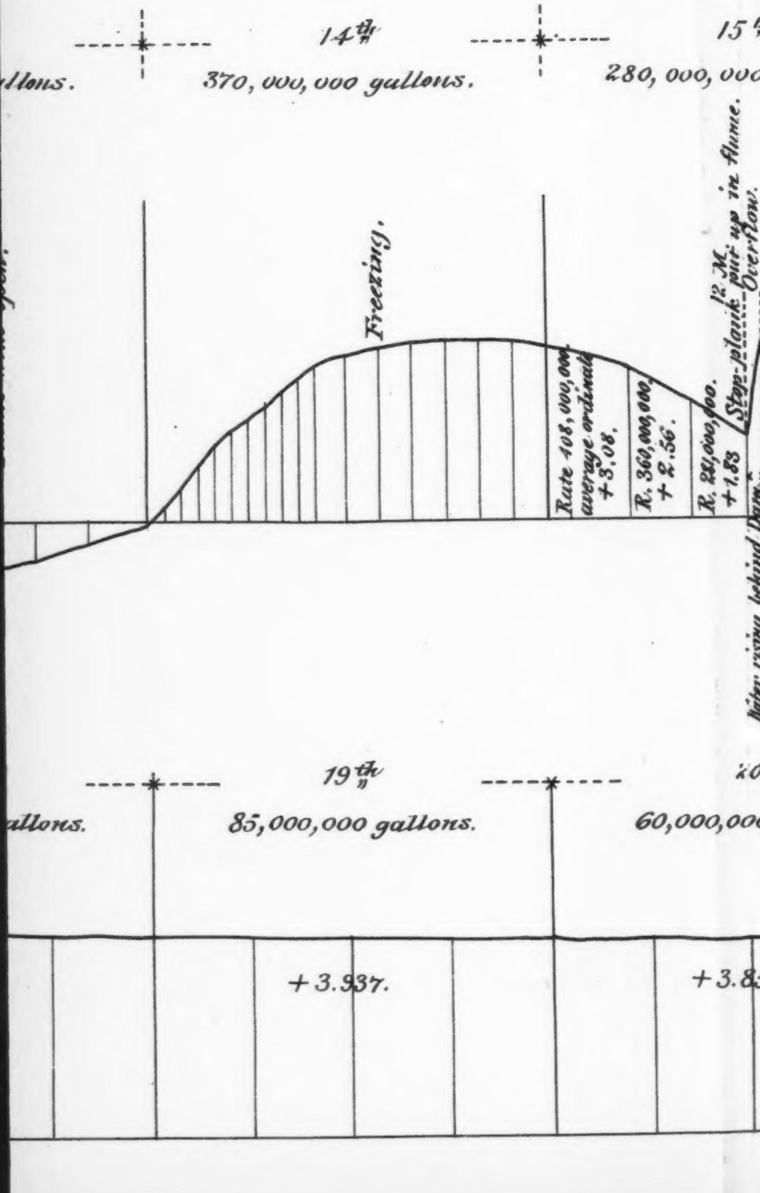
MONTH.	1879.				
	Total Yield of Sudbury River. Gallons.	Average Daily Yield. Gallons.	Rainfall. Inches.	Amount of Rainfall represented by flow in River.	
				Inches.	Percentage of total Rainfall.
January	1 698 200 000	54 780 600	2.478	1.249	50.40%
February	3 747 900 000	133 853 600	3.562	2.756	77.37 "
March	5 651 400 000	182 303 200	5.140	4.156	80.86 "
April	7 313 700 000	243 790 000	4.716	5.379	114.06 "
May	2 701 400 000	87 141 900	1.579	1.987	125.84 "
June	970 200 000	32 340 000	3.789	0.713	18.82 "
July	381 700 000	12 312 900	3.933	0.281	7.14 "
August	958 300 000	30 912 900	6.509	0.705	10.83 "
September	330 300 000	11 010 000	1.878	0.243	12 94 "
October	171 500 000	5 532 300	0.809	0.126	15.57 "
November	482 500 000	16 083 300	2.682	0.355	13.24 "
December	1 121 800 000	36 187 100	4.344	0.825	18.99 "
	25 528 900 000	69 942 200	41.419	18.775	45.33 "

MONTH.	1880.				
	Total Yield of Sudbury River. Gallons.	Average Daily Yield. Gallons.	Rainfall. Inches.	Amount of Rainfall represented by flow in River.	
				Inches.	Percentage of total Rainfall.
January	2 716 000 000	87 612 900	3.566	1.998	56.03%
February	4 054 400 000	139 806 900	3.980	2.982	74.92 "
March	......	......	......	......	......
April	......	......	......	......	......
May	......	......	......	......	......
June	......	......	......	......	......
July	......	......	......	......	......
August	......	......	......	......	......
September	......	......	......	......	......
October	......	......	......	......	......
November	......	......	......	......	......
December	......	......	......	......	......
	......	......	......	......	......

The rainfall since November, 1876, is an average of measurements at five places on the Sudbury water-shed.


Feb. 12th
3,700,000 gallons
in 24 hours.
13th
32,600,000 gallons.
Flow over one weir in flume.
Crest 145.11.
6 P.M. 3 Weirs in flume.
Crest 145.74.
Commenced thawing.
Heavy rain.
Weirs removed 2 P.M.
Flume wide open.
Elevation 146.
0.


17th
150,000,000 gallons.
18th
100,000,000 gallons.
Average ordinate +4.38.
+3.987.
146.
0.



14th
370,000,000 gallons.
280,000,000
Freezing.
Rate 408,000,000 average ordinate +3.08.
R. 360,000,000 +2.56.
+1.83
12 M. Stop-plank put up in flume.
Overflow.
19th
85,000,000 gallons.
60,000,000
+3.937.

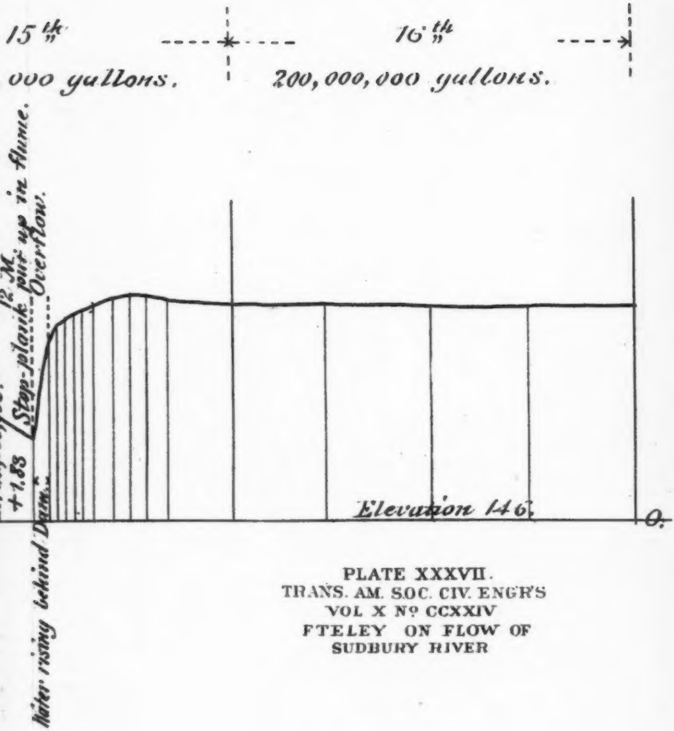


PLATE XXXVII.
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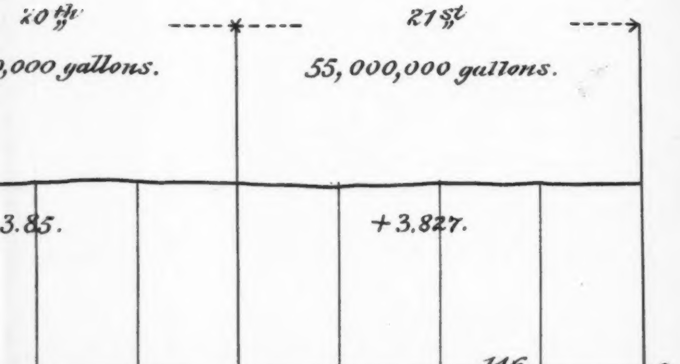
FTELEY ON FLOW OF
SUDBURY RIVER



Years.	Flow for the Whole Year. Total yield of River. Gallons.	Av. daily yield. Gallons.	Av. yield in cub. ft. per second per sq. mile of drainage area.	Total Rainfall. Inches.	Rainfall Collected. Inches.	Rainfall Collected. Per-centage.	T
1875........	27 593 700 000	75 599 200	1.50	45.490	20.418	44.88	3 7
1876........	32 309 900 000	88 278 400	1.76	49.563	23.908	48.24	2 4
1877........	34 444 750 000	94 369 200	1.88	44.018	25.487	57.90	2 4
1878...	41 202 000 000	112 882 200	2.25	57.931	30.487	52.63	3 0
1879........	25 528 900 000	69 942 200	1.38	41.419	18.775	45.33	1 8
1880.......	16 561 600 000	45 250 200	0.92	38.177	12.487	32.71	1 1
Averages...	29 606 810 000	81 040 500	1.615	46.100	21.927	47.56	2 4

Years.	Maximum Flow on any Day. Flow for the day. Gallons.	Maximum Flow on any Day. Yield in cub. feet per second per sq. mile of drainage area.	Minimum Flow in any Month. Average daily flow. Gallons.	Minimum Flow in any Month. Yield in cub. feet per second per sq. mile of drainage area.	Minimum Flow in a… Average daily flow. Gallons.	c… se… mi…
1875........	970 100 000	19.30	abt. 8 000 000	0.16	....	
1876........	2 080 000 000	41.39	14 229 000	0.28	4 000 000	
1877........	1 109 800 000	22.08	4 633 300	0.09	1 800 000	
1878........	784 600 000	15.61	9 983 900	0.20	5 300 000	
1879........	1 080 000 000	21.36	5 500 000	0.11	....	
1880........	....	.....	6 280 000	0.13	....	
Averages...	1 204 900 000	23.95	8 104 400	0.16	3 700 000	

WATER - SHED.

...ected.	Flow for July, August, September and October.					
	Total Flow.	Av. daily yield.	Cub. ft. per second per sq. mile of drainage area.	Total Rainfall.	Rainfall Collected.	
Per-...tage.	Gallons.	Gallons.		Inches.	Inches.	Per-centage.
4.88	3 770 000 000	30 650 400	0.60	17.38	2.790	16.05
8.24	2 411 200 000	19 603 300	0.39	17.709	1.784	10.08
7.90	2 439 350 000	19 832 100	0.39	15.471	1.805	11.67
2.63	3 075 200 000	25 001 600	0.50	17.616	2.276	12.92
5.33	1 841 800 000	14 974 000	0.30	13.129	1.355	10.32
2.71	1 150 800 000	9 356 100	0.19	15.624	0.867	5.55
7.56	2 448 060 000	19 902 900	0.40	16.155	1.813	11.22

...m Flow in any one Week	
...rage ... flow. ...lons.	Yield in cub. feet per second per sq. mile of drainage area.
.....	......
...0 000	0.080
...0 000	0.036
...0 000	0.105
.....	......
.....	......
...0 000	0.074

Drainage area previous to 1879........... 77.75 sq. miles.

" " for " .... 78.24 " "

Discussion on Rainfall and the Flow of Streams.

J. James R. Croes.—The Committee on the Gauging of Streams have been for some time urging upon members of the Society and other persons in positions which enable them to collect such data, the desirability of taking accurate and continuous measurements of the flow of streams of known water-shed, in connection with gaugings of the rain-fall. They take great pleasure in presenting the interesting paper from Mr. Fteley, giving the results of the most accurate and long-continued observations of this kind that have been made in this country.

These gaugings were instituted by order of Joseph P. Davis, M. Am. Soc. C. E., then City Engineer of Boston, in whose preliminary reports on an additional supply for that city, in 1873 and 1874, may be found a valuable compilation of facts and arguments with reference to the available quantity of water which may be depended upon from a known water-shed. It is only by continuous and long-continued observations that the actual capacity of supply of a stream can be obtained, and we hope that the publication of this record will incite other engineers to institute such observations and communicate the results to the Society for publication.

The past summer has been one of extreme drought throughout the North-eastern and Middle States, and there is little doubt that its effects will be felt during the coming year very seriously.

Where there is considerable storage accommodation, the ill effect of a dry season is not felt to its full extent during the drought, but some time after the rains have begun. While there is a deficiency of rain-fall, the stored water, both in the reservoirs and in the ground is drawn upon to supply the demand, and not only the first rains, but those which fall for some time after are absorbed in filling up the depleted storage. It is not uncommon also to lose a large proportion of the first rains by their rapid flowing off from either parched or frozen ground.

The extent of the present dry term may be judged to some extent from a short statement of facts collated from the newspapers of the past month.

In Kittery, York and Wells in Maine, wells and springs which have not failed for fifty years are now dry, and some farmers have to drive their stock two and three miles to water. At Nashua, New Hampshire, the mills are running on half time, owing to the scarcity of water. At Manchester,

New Hampshire, the source of supply, Lake Massabesic is lower than it has been for many years. The outlet is being deepened, and the city is supplied by water from the Merrimac river, pumped into the reservoir of one of the manufacturing companies. At Kingston, New York, wells and cisterns are dry, and water is carted from a distance, and sold in the streets by the tubfull. On the Delaware and Hudson Canal, navigation has been discontinued for some weeks, and most of the mills along the streams have entirely suspended work. Owing to the long drought it is said that less than one-half the usual amount of lumber will be rafted from the upper Delaware this fall.

At Mechanicsville, New Jersey, mills are stopped and many employees thrown out of work. At Reading, in Pennsylvania, the city has been deprived of water for ordinary household uses. The Chester, Pennsylvania, Water Works are unable to supply the town.

At Altoona, Pennsylvania, springs have dried up which were never known to fail before. At Paterson, New Jersey, the Passaic river is so low that it has been necessary to stop the mills for a day to get water to fill the reservoirs for city supply, On Staten Island, wells and cisterns have become dry, and water is in many instances compelled to be carted long distances. In Baltimore, the water in Lake Roland has been more than six feet below the dam, notwithstanding the pumping of from five to ten millions of gallons into it daily from the Gunpowder river. At Petersburgh, Virginia, the water in the reservoir has become so impure from drought that the Board of Health has forbidden its use for drinking purposes. At Richmond, Virginia, the water is so scarce that one reservoir was empty, and the other held so little that a portion of the city has been cut off from the supply, and great inconvenience caused. In New York City the storage reservoirs have been drawn very low, and unless copious rains soon fall, the effects of the drought will be very severely felt. The Brooklyn supply is so reduced that i has been necessary to make arrangements for pumping water from wells into the conduit.

Now, what we want is, to know at what intervals of time such seasons of water famine may be expected, and how their bad effects may be guarded against, and to what extent storage can be relied upon. The only way to find this out is by having such careful observations as Mr. Fteley has given us, and analyzing and comparing them.

THE CHAIRMAN (Vice-President Welch).—In the absence of the author

of the paper, the Chairman of the Committee on the Gauging of Streams will give a summary of the principal facts stated in the paper, with regard to the ratio between the rain-fall and the flow of the stream.

J. J. R. Croes.—During the six years in which these continuous observations have been made on the Sudbury river, with a water-shed of 77.764 square miles, the rain-fall has varied from 38.177 inches to 57.931 inches, and the discharge of the stream from 12.487 to 30.487 inches per year on the water-shed. The percentage of rain-fall which reached the stream at the gauging point varied from 32.71 per cent. to 57.90 per cent., the flow for the five years being 47.56 per cent. of the total rain-fall.

F. Collingwood.—Do not the gaugings show that in the years of least rain-fall the percentage flowing off was least?

J. J. R. Croes.—They do not altogether. The least percentage of the rainfall flowed off in 1880, when the rain-fall was the least, but in 1875 the percentage flowing off was less than in either 1877 or 1879, which were years of less rain-fall. The greatest percentage flowed off in 1877, when the rain-fall was 13.9 inches less than the greatest rainfall. No ratio can be traced between the amount of rain and the proportion of that rain which will reach the streams.

Joseph P. Davis.—The proportion which flows off will depend upon the manner in which the rain-fall is distributed throughout the year.

Ashbel Welch.—What ratio does the greatest flow bear to the extreme low water discharge?

J. J. R. Croes.—It appears that the least discharge of the stream in any one week was at the rate of 1 800 000 gallons per day, or 0.036 cubic feet per second per square mile of drainage area, while the maximum discharge noted was 2 080 000 000 gallons per day or 41.39 cubic feet per second per square mile, being 1 150 times the least flow.

Ashbel Welch.—The amount of water which passes any point on any one day can not be considered a guide to the yield of the stream, particularly in cases where there are dams and mill ponds on the stream. The water may be held back by them, and cause an apparent discharge really much less than the actual flow of the stream.

Joseph P. Davis.—For that reason the minimum discharge of the Sudbury river is not taken at the rate of flow for any one day, but at the mean discharge for several days during the dryest time. The tables given by Mr. Fteley show the flow for a week in September, 1877, to have averaged only 0.036 cubic feet per second per square mile.

J. J. R. Croes.—That is a very small yield for a water-shed of that area. The notes which the committee published last year in their report (Proceedings A. S. C. E., Vol. V, p. 110) showed nothing as low as this except from an area of 20 square miles. We have received from Mr. W. R. Hutton (see p.) some notes of Maryland and Virginia rivers which show in the case of the Potomac river so extraordinarily small a flow, that that stream seems to be of an entirely different character from any Eastern rivers of which we have records. The flow at Cumberland where the drainage area is 1 364 square miles was stated, in 1837, by Mr. Patterson to be 25 cubic feet per second, or only 0.0183 cubic feet per second per square mile. This is not more than one-tenth of what we shall expect from the gaugings of rivers of the same water-shed in the Eastern States. The same stream at Great Falls, 17 miles from Washington, where the drainage area is 10 964 square miles, discharged in August, 1855, only 1 063 cubic feet per second, or 0.097 cubic feet per second per square mile, being about one-fifth of the discharge from nearly the same drainage area in the Connecticut river at its lowest recorded stage in August, 1876. J. H. Harlow, M. A. S. C. E., has furnished the results of a gauging of the Ohio river at Pittsburgh by himself in October, 1879. The discharge was then the least known for twenty-five years. The average of two measurements was 2 271 cubic feet per second, assuming the area drained to be as stated by Mr. W. Milnor Roberts in his report (Ex. Doc., 72, H. of R., 41st Congress, 3d Session, page 160) 19 900 square miles, this discharge was at the rate of 0.114 cubic feet per second per square mile. This shows a marked similarity between the low water discharge of the Ohio and the Potomac, the headwaters of both of which streams are about of the same meridian.

Clemens Herschel.—The flow of the Connecticut river near Dartmouth, New Hampshire, was gauged on October 9, 1880, by means of floating tubes in a selected channel. The result which was probably correct within five per cent., was 1 006 cubic feet per second. The drainage area was about 3 287 square miles, and the discharge was therefore 0.306 cubic feet per second per square mile.

J. J. R. Croes.—As to maximum flow, the Sudbury river shows a very small quantity, when compared with several other streams of the same water-shed. The greatest flow noted by Mr. Fteley was in March, 1876, when the drainage was 42.17 cubic feet per second per square mile. Against this we have the flood of 1843, in Flat river, R. I.,

mentioned by Mr. Shedd, of 120.75 cubic feet per second per square mile from an area of 61 square miles, and the Rock creek flood given by Mr. Hutton as 126.4 cubic feet per second per square mile from an area of 77.5 square miles. In this connection, the attention of members interested in this subject may be called to the interesting discussion on the flood discharges of stream by the Engineers' Club of Philadelphia, and published in their proceedings (Vol. I., pages 146 and 194).

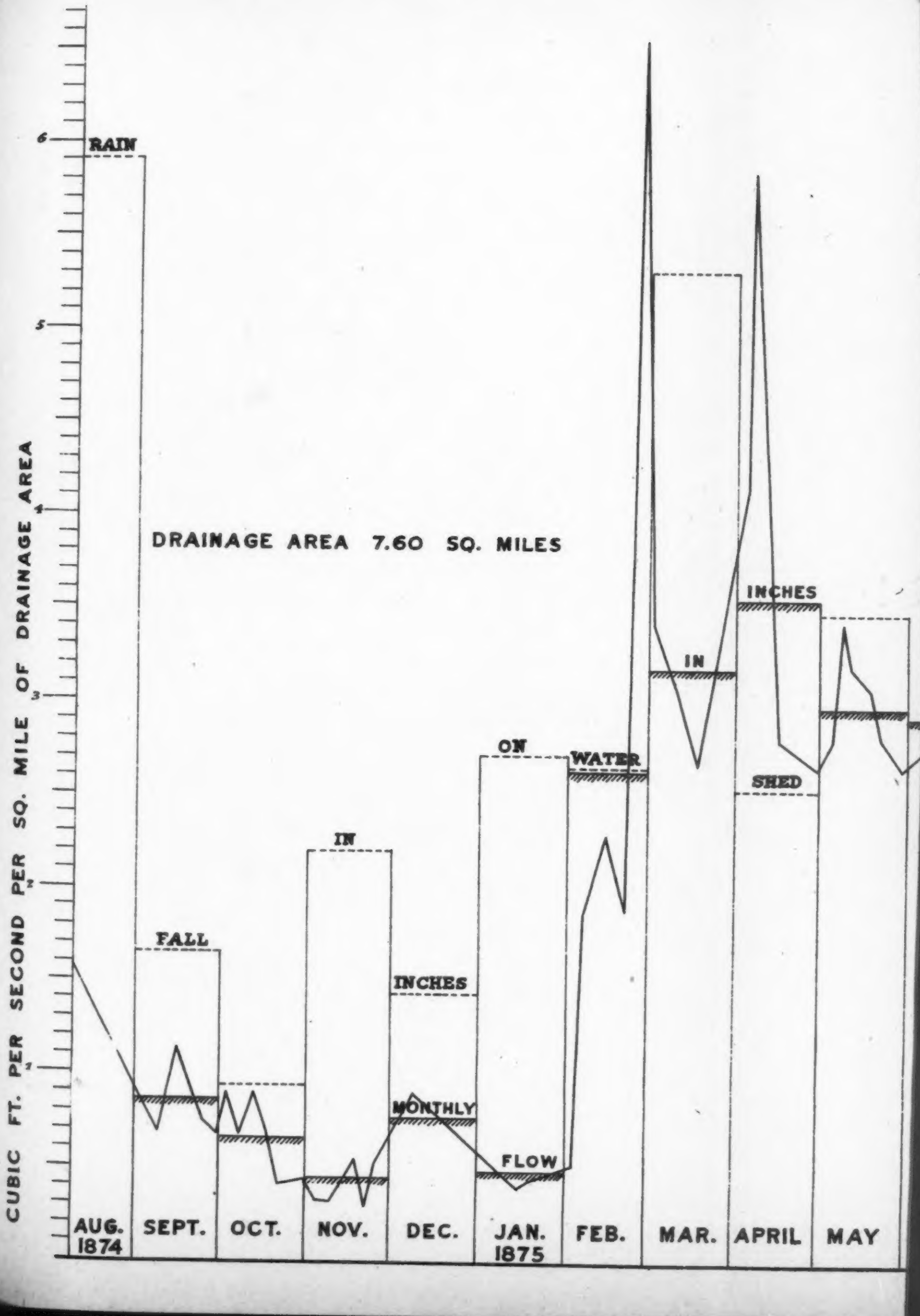
JOSEPH P. DAVIS.—In the construction of the dams for the storage reservoirs on the Sudbury river, the overflow weirs were proportioned to carry off, without injury, floods of 160 cubic feet per second per square mile. Although the gaugings had not shown a discharge of more than one-fourth of that amount, the examinations of Mr. James B. Francis proved that such a flood was probable at some time.

MARSHALL M. TIDD.—The discharge of water from Horn Pond in Massachusetts, one of the tributaries of the Mystic supply of the City of Boston, was measured at intervals during the years 1874 and 1875. The table on the next page and plate XXXVIII show the fluctuations of the discharge and approximately the aggregate discharge. The rate of flow is given in cubic feet per second per square mile of the drainage area of the pond, which is 7.60 square miles; the monthly discharge is in inches in depth on the water-shed.

The discharge for the year ending September 1, 1875 was equivalent to 26.362 inches on the water-shed, or at the rate of 14.76 cubic feet per second. The maximum flow was on February 25, 1875, and was at the rate of 49.82 cubic feet per second, or 6.55 cubic feet per second per square mile. The minimum flow was on November 21, 1874, and was at the rate of 2.21 cubic feet per second, or about 0.30 cubic feet per second per square mile.

Flow of Horn Pond.

Date of Observation.	Discharge per cu. ft. per second per sq. mile.	Discharge per month in inches on Water-shed.	Rain-fall.	Date of Observation.	Discharge per cu. ft. per second per sq. mile.	Discharge per month in inches on Water-shed.	Rain-fall.
1874.				1875.			
Aug. 8......	1.577	....	6.68	April 3......	4.168		
Sept. 8......	0.694			" 5......	5.851		
" 14......	1.151			" 15......	2.807	4.012	2.87
" 16......	1.134	0.990	1.87	" 29......	2.667		
" 24......	0.756			May 4......	2.808		
" 29......	0.694			" 7......	3.439		
Oct. 2......	0.921			" 10......	3.206		
" 7......	0.694			" 17......	3.101	3.368	3.93
" 12......	0.921	0.744	1.06	" 21......	2.808		
" 17......	0.694			" 29......	2.667		
" 21......	0.417			June 9......	2.808		
" 30......	0.450			" 12......	3.748		
Nov. 4......	0.328			" 19......	2.808	3.308	......
" 9......	0.328			" 22......	2.667		
" 17......	0.567	0.505	2.5	July 8.....	2.667		
" 21......	0.291			" 15......	2.239	2.570	......
" 24......	0.533			" 24......	1.854		
Dec. 8......	0.921	0.874	1.62	Aug. 4......	2.031		
1875.				" 9......	2.230		
Jan. 14......	0.417	0.553	3.06	" 14......	1.854	2.859	......
" 18......	0.450			" 24......	3.967		
Feb. 2......	0.533			Sept. 4......	2.230		
" 5......	1.854			" 24......	2.230	2.345	......
" 13......	2.289	2.982	3.0	Oct. 5......	1.854		
" 20......	1.854			" 11......	2.808	3.010	......
" 25......	6.5564			Nov. 1......	3.101	3.493	......
Mar. 1......	3.439			Dec. 24......	3.101	3.486	......
" 9......	3.100	3.597	6.0	1876.			
" 17......	2.667			Jan. 22......	2.808		



RAIN
FALL
IN
INCHES
ON
WATER
IN
INCHES
SHED
MONTHLY
FLOW
DRAINAGE AREA 7.60 SQ. MILES
CUBIC FT. PER SECOND PER SQ. MILE OF DRAINAGE AREA
6
5
4
3
2
1
AUG. 1874
SEPT.
OCT.
NOV.
DEC.
JAN. 1875
FEB.
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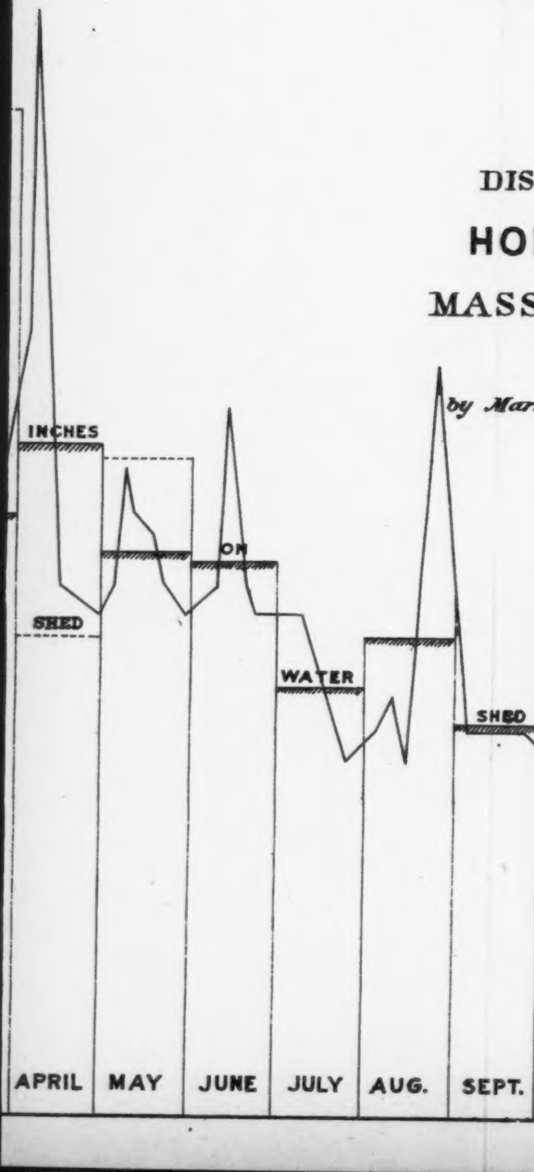

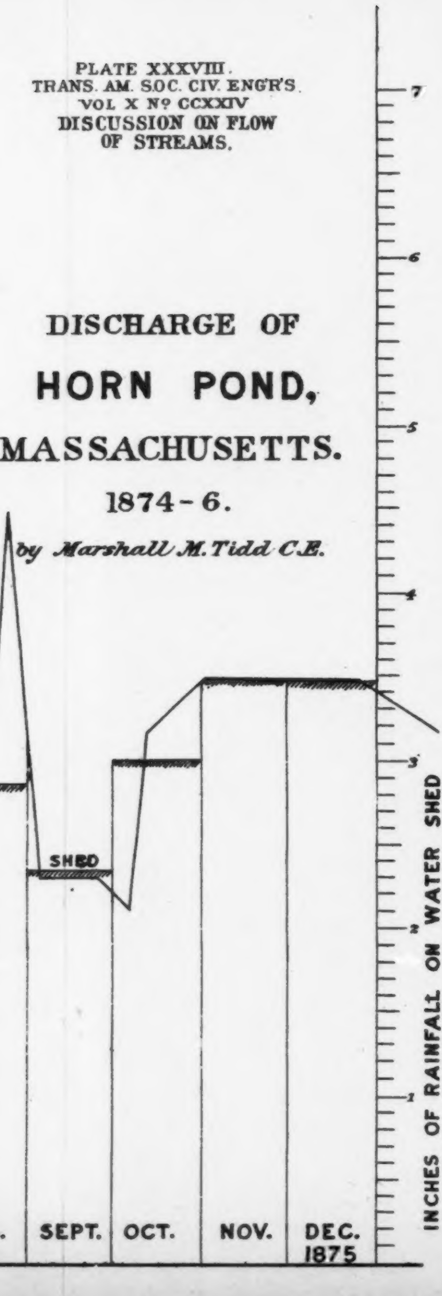
PLATE XXXVIII.
TRANS. AM. SOC. CIV. ENG'R'S.
VOL X No CCXXIV
DISCUSSION ON FLOW OF STREAMS.
DISCHARGE OF
HORN POND,
MASSACHUSETTS.
1874 - 6.
by Marshall M. Tidd C.E.
SHED
SEPT.
OCT.
NOV.
DEC. 1875
7
6
5
4
3
2
1
INCHES OF RAINFALL ON WATER SHED

F. Collingwood.—With reference to the proportion of the rain-fall which flows off through the streams, I think it will be found that it is least during the season when plowing is going on. The ground then absorbs more water, owing to the breaking up of the surface.

The percentage depends largely also on the distribution of the rain-fall. More water will reach the streams when there is a succession of light rains, keeping the ground full, than when the same amount of rain is precipitated in a few storms.

J. J. R. Croes.—In this latitude, the least percentage of the monthly rain-fall which reaches the streams is during the months of July and August. From October to April the ratio of rain to flow cannot be depended upon for any deductions, in consequence of a part of the precipitation being in the form of snow, which lies for some time. Between December and April the flow of the streams is likely, in two months, at least, to be from 100 to 150 per cent. of the precipitation. The flow of May and June is more apt to represent the normal discharge.

William R. Hutton.—The data from which the table on the following page has been prepared have been gathered from official reports of officers of the United States Coast Survey and army.

The flow discharges of the Potomac are not more than approximations.

Ashbel Welch.—The river Delaware, at the driest seasons, discharges a little less than 2 000 cubic feet per second. In the great floods about 350 000 cubic feet per second, nearly 200 times more than the minimum. The drainage area above my point of observation is somewhere between 6 500 and 7 000 square miles. In regard to Mr. Collingwood's suggestion, my observation is that when gentle rains come through the dry seasons they do not affect the streams at the time at all; for instance, in the months of September and October of this year we had, during that time, 3½ inches of rain, but the brooks were not affected perceptibly; it all went into the ground or evaporated. On the other hand, in some districts that I am acquainted with a hard rain passes off within a few hours. I know of one small district near the place where I live, where the soil is red shale, almost impervious to water; the hills are covered with very little vegetation, and when a hard rain comes the whole amount passes off in six or eight hours, and a little stream draining a few square miles will discharge, for a short time, 5 000 or 6 000 cubic feet per second.

DISCHARGE OF STREAMS—RATIO OF HIGH AND LOW WATER DISCHARGES TO AREA DRAINED.

CONTRIBUTED BY WILLIAM R. HUTTON.

		Extreme Length of Area Drained —Miles.	Area Drained—Square Miles.	Discharge in Cub. feet per Second.	Cubic feet per Second per Sq. Mile.	Date.	Authority.	Remarks.
1	Potomac River at Cumberland, Md.	65	1 364	25	0.0183	1873	Patterson	Lowest water. Ordinary low water of dry years is more than twice as much.
2	" "	65	1 364	11 456	84.			High flood.
3	" "	65	1 364	17 900	131.	Nov., 1877.		Extremely high water. Great flood.
4	" Dam No. 5	153	4 640	363	0.0783			Very low water—approximate.
5	" "	153	4 640	72 000	15.65	Feb., 1870.		High flood.
6	" "	153	4 640	92 772	20.00			Extraordinary flood.
7	" Great Falls, Md.	244	10 964	1 063	0.097	Aug., 1855.	Hutton	Lowest. Ordinary low water of dry seasons 50% more.
8	" Georgetown, D. C.	260	11 124	175 000	15.73	Spring, 1852		Extraordinary flood 1852; those of 1870 and 1877 were considerably higher, but no data for computations. This is approximate.
9	Rock Creek at Hoyle's Mill, D. C.	18	64.4	29.3	0.458	Oct., 1852.	Meigs	Ordinary summer water.
10	" " "	18	64.4	7.5	0.114			Very low water—rare.
11	" Georgetown, D. C.	26	77.5	9 790	126.4			High flood.
12	Kanawha River on Charleston pool, Va.	270	8 900	1 100	0.123	1838.	Gill	Extreme low water.
13	" " "	270	8 900	94 460	10.61	July 13, 1875	Scott.	Flood of 26.5 feet.
14	" " "	270	8 900	118 291	13.29	Aug. 3, 1875	Scott.	Flood of 32.8 feet.
15	Greenbrier River, mouth of Howard's Creek, Va.	60	810	97	0.120	Sep. 5, 1826	McNeil	Very low water.

George W. Dresser.—I would like to ask Mr. Welch if he thinks that in the case of the gentle rains that he refers to, where the water is apparently all soaked into the ground, the effect of the water is felt afterwards in the stream.

Ashbel Welch.—Yes, sir; it disappears entirely, but it ultimately reaches water-bearing strata, and then it comes out, and if it goes into the ground it remains for a time, but it will appear in the stream sooner or later. In the case of the hard rains, it does not have time to get down; it simply runs off.

I remember on one occasion a rain in which about 12 inches fell in about as many hours in one night. It was not determined by a rain gauge, because the rain gauges ran over, but by different tubs, and pails, and troughs apart from buildings. I was satisfied that during these 12 or 14 hours about a foot fell, but it was over a very narrow district. On either side of it was a very hard rain, but none like that, and in that district it caused a very great deal of damage, and one part of the damage was a break in the canal of which I had charge, near Boundbrook.

Samuel L. Smedley.—What year was that?

The Chair.—It was in August, 1843. The most destructive rain storms I have seen have been in August, and next to that, July.

Samuel L. Smedley.—Has there been any change in the amount of rain-fall since the cutting off of the forests?

Ashbel Welch.—When I first knew the Delaware, nearly half a century ago, the minimum flow was probably 4 000 cubic feet per second—twice as much as it is now. The discharge in the highest flood ever known before 1841, that of 1787, was not more than two-thirds as much as that in the great flood of 1841.

J. J. R. Croes.—Has there been any great flood since 1841?

Ashbel Welch.—There have been two, one of which was nearly, if not quite as high. The flood of 1841 and two subsequent floods must have discharged nearly twice as much water as any previous floods since 1787, and 50 per cent. more than the flood of 1787. I suppose that there is not, at the lowest stages, more than half the water in the Delaware that there was half a century ago, and that the highest floods carry off 50 per cent. more per hour than any flood known before 1841.

J. J. R. Croes.—Are these figures the result of measurement?

Ashbel Welch.—The 2 000 cubic feet is measurement some years ago. The 4 000 cubic feet is a very rough measurement at the time in

various ways, none of them accurate, but still corroborating each other, so that I probably get the result within 10 per cent. of the truth.

Samuel L. Smedley.—In regard to the Delaware, I would like to know whether you have any record of rain-fall over an extended period?

Ashbel Welch.—No, sir. Very few rain gauges were kept at that time. I had a conversation with Professor Henry several years ago on the subject of cutting off the woods in relation to the rain-fall. He had paid some attention to that subject, and he said, so far as he could see, the cutting off of the woods did not diminish the rainfall; that there was just as much fell afterwards as before. He said, in regard to places that came under his notice, that the difference is this: while the country was covered with woods and swamps, and while these swamps were covered with leaves and vegetable matter, the rain that fell stopped there, and ran off gradually; but after the country was cleared it ran off immediately, but the actual rain-fall was as great in one case as the other. It would be interesting to test this question still further.

Julius E. Hilgard.—In regard to data on which this opinion of Professor Henry's was based, I may say that they were observations which have been kept at Marietta, Ohio, for 50 years, and show that during the decennial periods the rainfall at that place was identically the same. The effects of cutting off the woods have been very clearly felt. The wells have given out, the springs dried up in the summer; brooks that always had a flow of water in them are entirely dry in the summer, and agriculture has been very much affected. Still, the rain-fall has actually been the same. I only wish to mention the precise data.

Ashbel Welch.—There is one consolation about this matter: while the cutting off of the woods and the clearing up of the land causes the water to run off a good deal faster, yet, as the land is further cultivated and converted from pasture with shallow soil to meadow or ploughed land with deep soil, the soil is made more retentive by increasing the thickness of the sponge on its surface, and it gives off the water more gradually, so that as the country is cultivated this inconvenience of exceedingly low streams and wells is somewhat ameliorated.

Thomas C. Clarke.—That is not the case all through the West. In a prairie country, where there is hardly any timber, it is well known that the prairie grass and sod acts like a sponge, whereas when cultivation takes place the drainage leads the water off rapidly.

Ashbel Welch.—In this part of the country, in most cases, after the

land is cleared, it is left hard and almost naked, with no depth of vegetable mould. From this the water runs off immediately. Plough that land and make it porous, and fill it with roots, and cover it with vegetable mould of some depth, and it will absorb a great deal of water and give it off gradually. I can see that cultivation may operate the other way on the prairies. When you destroy the prairie grass, and substitute a less rank vegetation, the depth, and porosity, and retentiveness of the mould may be diminished. So Mr. Clarke's view and mine do not conflict. If you watch a hillside in the rain, where the ground is uncultivated and hard, you will see the water running down in numerous little rills; but if the ground is cultivated and the mould deep, the same rain, if not very hard, will all go into the ground.

Octave Chanute.—Mr. Welch stated, as well as Mr. Hilgard, that Prof. Henry's opinion was that the annual rain-fall was not diminished by the diminishing of the forests. I would ask the Chairman whether he has any other facts that bear upon that subject, and which seem to confirm that opinion of Mr. Henry? If I remember correctly, in Mr. Marsh's book, entitled "Man and Nature," he takes the ground that the experience, more particularly of the old world, is that the rain fall does annually diminish in consequence of the cutting away of the trees, and instances the land about the Pyrenees between France and Spain, and the whole of Great Britain and Germany. The question is of great importance for us in this country, because as we proceed westward we know the rainfall diminishes; that while it is some 45 inches a year on the Atlantic seaboard, when the Missouri river is reached, the rain-fall diminishes to about 32 inches, and that at the 100th meridian, upon the edge of the arable portion of the United States, the rainfall does not exceed 28 inches, while on the plains about 500 miles west of the Missouri river, it drops down to 6 or 9 inches. The problem presented in that region is to compel a greater rain-fall. The soil is abundantly rich, but nothing can be grown without more moisture. As I say, it is of the greatest importance for us to know whether the cutting away of forests does diminish rainfall, and if by planting trees we can increase it.

Charles E. Emery.—There are some facts in regard to the great Sahara desert. It will be remembered that there are driven wells upon it, and that artificial oases are formed at those places, and that when water is thus brought to the surface, vegetation extends till sometimes rain-falls will take place in the neighborhood. That was the effect of

building the Suez Canal. I don't recollect the details, but in that direction there will be found some very valuable information on this subject.

J. E. HILGARD.—Marietta, the place mentioned, is the farthest place West where observations have been taken for a sufficient length of time to arrive at the facts. I am only speaking of observed facts. On the Atlantic slope of the Alleghanies there are many stations where meteorological observations extend for a longer period than that; for instance, in Providence, Rhode Island, by Prof. Caswell, which show the same fact. Those at Marietta were made by Mr. Andrews, the father of the present Professor Andrews, there. While they show that the average amount of rain has been the same, it may be questioned whether there might not be a change in its distribution; whether, for instance, there are now heavier rains at longer intervals. Classing them by weeks, throughout the year, has shown that there has been no material difference in the period covered by that series of observations. Those are all the facts that I know of.

In regard to the diminution of water in wells and streams in Europe, especially in Germany, in the region of East Prussia and the Baltic, a very late work has been published. We know in those countries there are much more numerous data to be obtained than here. I have only had time to look at it in a general way. The general facts are the same as here. The amount of rain-fall has not diminished, but its conservation has been affected by the clearing of the country. Some points that seem contradictory may be readily explained, while others, to me, are not susceptible of a physical explanation; for instance, that the cutting of the woods of so small an altitude on the great elevation of the Pyrenees should change the particular mode in which the vapor is condensed in passing those mountains.

Although the cutting off of the forests might produce a sensible effect on the condensation of vapor, yet, so far as the general distribution of rain-fall in the United States Territory is concerned, it is very obvious that the only effective mode of curing the rainless districts would be to remove the mountains. The supply of vapor comes from the Pacific Ocean, and as the atmosphere's circulation is from west to east, it is carried eastward and precipitated when it comes in contact with the Rocky Mountains, and that is what makes the Eastern slope dry in the summer. In winter, when the moisture-bearing air is colder, there is less precipitation on the Western slopes, and we have snows on the Eastern slope

where we have no rains in summer. The difference between the Eastern and the Western side of the Mississippi Valley is due to its rain fall being mainly derived from the vapor from the Gulf of Mexico, moving northeastward with the prevailing southwest winds of summer, parallel with the Alleghany chain of mountains. Hence the amount of rainfall on the Western and Eastern slopes of the Alleghanies is sensibly the same.

Ashbel Welch.—I ought to say that Professor Henry made the remark which I quoted when we were talking about the country east of the Alleghanies, and no doubt he had that country in his mind. He did not state the proposition as a universal one, and therefore it might be quite consistent with it that in the desert of Sahara, or in Egypt, the rain-fall might be increased by planting trees.

O. Chanute.—My idea was not to question the fact with respect to observations in this country, but to inquire, rather, whether they were substantiated elsewhere. It is clear that a few observations taken in the Atlantic slope for a period of 40 or 50 years are not to be relied upon exclusively to draw therefrom general conclusions. As to the effect of cutting off the trees, it is my opinion that those people who have held that the clearing of the forests diminishes the rain-fall, attribute the effect of the trees upon the rainfall, not so much to their height above the surface of the ground as to some chemical effect produced upon the atmosphere, perhaps that of the carbonic acid gas, which the leaves of the trees absorb, and which may increase the amount of condensation and precipitation of the clouds.

With respect to the other theory, which has been stated by Mr. Hilgard, I would call attention to the fact that the rainfall does not diminish over the plains from the west easterly, but from the east towards the west, and it diminishes with great rapidity over a particular belt of country. At 100 miles west of the Missouri river it is about 28 inches, but 400 miles west of this it is diminished to 9 inches, and in some localities it is only 6 inches. The clouds which bring the rains that fall over the plains come from the east and south, and not a drop, I think, passes west of the Rocky Mountains, the clouds having poured out part of their contents over the Middle and Western States as far as the 100th meridian, scud over the space west of this without dropping any rain, and are finally wrung dry by the cold summits of the Rocky Mountains.

J. J. R. Croes.—The observations to which Mr. Hilgard alludes are probably those of Sir Gustav Wex, in his treatises on the decrease of

water in springs, creeks and rivers, contemporaneously with an increase in height of floods in cultivated countries. The first treatise was published in 1873, the second in 1879. The latter has been translated by Gen. G. Weitzel, U. S. A., and issued from the the Government printing office.

From observations at 51 stations on 13 rivers, during periods ranging from 20 to 150 years, he reaches the conclusion, that not only the mean flow, but also the maximum and minimum discharges are annually decreasing. This, at least, would appear from his statements, notwithstanding the title of his book. He considers also that this decrease of flow is due to a decrease of rain-fall. In support of this opinion he quotes only two instances, one at Bodenbach, in the Erz Mountains of Bohemia, where two periods of twenty-two years each are compared, showing a decrease in the annual mean of 1.26 inches; the other at Geneva, for two periods of 35 and 11 years, showing a decrease of 3.3 inches.

Wex's conclusions have been disputed by several German scientists. As regards the amount of discharge we have not, in America, observations made with accuracy extending over a sufficient time to determine whether it is increasing or diminishing.

As for the rain-fall, it is certainly not diminishing on the seaboard in this latitude.

Mr. Daniel Draper, the Director of the Central Park Meteorological Observatory, discussed this subject at some length in his reports for 1873 and 1876. The conclusion reached by him was, that although there are large variations from year to year, no perceptible change occurs when long periods are compared.

In fact, so far from the rain-fall diminishing it appears to be at present increasing here.

The mean rain-fall at Philadelphia from 1827 to 1844, 18 years, was 43.31 inches; from 1845 to 1861, 17 years, was 45.18 inches, and from 1862 to 1879, 18 years, was 48.31 inches.

In New York City the mean precipitation from 1836 to 1848, 13 years, was 40.47 inches; from 1849 to 1862, 14 years, was 48.39 inches, and from 1862 to 1876, 14 years, was 49.53 inches.

At Providence, R. I., taking 15 year periods, the mean rain-fall was, from 1832 to 1846, 39.50 inches; from 1847 to 1861, 43.97, and from 1862 to 1876, 48.02 inches.

At Boston, from 1850 to 1865, 14 years, it was 51.09 inches, and from

1866 to 1879, 14 years, it was 49.51 inches. In this case there was a small decrease. In all the others a decided increase.

The danger of drawing conclusions as to the average discharge of streams, from partial observations or too short periods of time, is well illustrated from the records of the flow of Lake Cochituate, one of the Boston sources of supply. From 1858 to 1868, 11 years, the mean flow was 20.18 inches, and from 1869 to 1879, again 11 years, it was 21.13 inches, a decided increase. But if we begin with 1857, a year of large flow, and end with 1880, a year of very small flow, the mean for the first 12 years is 22.38 inches, and for the second twelve years is 20.25 inches, showing an equally decided decrease of flow in the later period.

William R. Hutton.—The following note by the late M. Belgrand, in charge of the water supply of Paris, may be of interest in connection with this subject. He remarks that the seasons from 1857 to 1865 were of extraordinary dryness in France, as shown by the following table, which gives the number of days that the river Seine was below the zero of the gauge of La Tournelle, the reference for Paris, which is supposed to be the lowest water known in 1719.

From 1732 to 1799, 67 years,	average..	0.57	days	per annum.
1800 " 1826, 26 "	" ..	10.67	"	"
1826 " 1856, 30 "	" ..	2.23	"	"
1856 " 1865, 9 "	" ..	100.00	"	"

Alfred G. Compton.—It seems to me that the observation of the rain-fall at a small number of stations within a water-shed does not furnish sufficient data to estimate the yield from the whole area. There are so many local storms of small area that measurements of rain-fall at a single point do not give the average of a large district, like the drainage area of the Delaware river for instance. The measurement of the flow of a stream gives us correct data independent of the rain-fall.

Joseph P. Davis.—Gaugings of a stream, if they extend over a sufficient length of time to include seasons of great drought, are undoubtedly the most reliable, but usually the engineer is called upon to make estimates of the yield of water-sheds where no gaugings of the streams have been made, so that, practically, he has to rely upon the record of rain-fall, and it is found that a single rain gauge, kept for a number of years, within the area, or in its vicinity, gives a very good average, in most cases, of the rain on the water-shed.

J. J. R. Cross.—The Department of Public Works of New York City assumes the rain-fall at the Boyd's Corners Saratoga Reservoir as the basis of computation. This is in the Croton Valley, 23 miles north of the Croton Dam, and 16 miles from the Hudson river, 550 feet above tide level. There were no other rain gauges kept in the Croton Basin until 1879, when one was established at the Middle Branch Reservoir, 8 miles southeast of Boyd's Corners.

Between that point and New York City some rain gauges have been kept, the record of which is appended. Peekskill, Sing Sing and Tarrytown are on the Hudson river. The other points are inland. Boyd's Corners and the Middle Branch Reservoir are the only points in the Croton Basin. The ordinates of each point are given in miles, referred to the New York City Hall and a meridian passing through it.

	Boyd's Corners. 51 N. 14 E.	Middle Branch. 44 N. 20 E.	Sing Sing. 30 N. 8 E.	Peekskill. 40 N. 3 E.	Tarrytown. 24 N. 8 E.	White Plains. 21 N. 12 E.	New York City.
1863	....	....	....	....	42.35	....	57.03
1864	....	....	....	....	38.73	....	47.61
1865	....	....	....	....	49.73	....	62.98
1866	....	....	75.70	....	47.30	....	52.23
1867	50.07	....	88.02	....	45.73	....	54.66
1868	50.33	....	93.42	....	53.48	....	64.03
1869	48.36	....	82.98	....	50.80	....	45.47
1870	44.63	....	....	....	47.51	....	39.25
1871	48.94	....	....	....	60.39	....	51.26
1872	40.74	....	....	....	42.75	....	42.49
1873	43.87	....	....	....	50.44	41.60	47.99
1874	42.37	....	....	42.00	49.38	60.30	45.83
1875	43.66	....	....	45.73	59.38	63.80	40.90
1876	40.68	....	....	41.46	47.78	63.50	41.77
1877	46.03	....	....	43.52	45.58	61.95	40.18
1878	54.14	....	....	41.92	47.86	64.50	48.66
1879	46.08	44.27	....	40.10	42.28	63.60	....
1880	38.52	35.45	....	35.96	36.46	59.43	....